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O A L S BULLETIN 9

TECTONIC ANALYSIS OF FOLDS
IN THE
COLORADO PLATEAU OF ARIZONA

by
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and
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FOREWORD

This Bulletin is published in furtherance of the purposes of NASA grant NGL 03-002-313 entitled "Research for Application of Remote Sensing to State and Local Governments." The purpose of the grant is to assist, with the use of NASA high-altitude photography and satellite imagery, state and local agencies whose responsibility lies in planning, zoning, and environmental monitoring and/or assessment of energy and mineral resources.

This report is the ninth in a series of publications designed to present information bearing on remote sensing research and applications in Arizona. This present study utilized small-scale LANDSAT-1 imagery as a field base for mapping the distribution of monoclinal folds and, to a lesser extent, anticlines and synclines within an 35,000 square-mile region in the Colorado Plateau tectonic province of Arizona. A literature search was conducted to add to this map the major fold structures in the Plateau that lack a significant photogeologic expression. The resultant map pattern is analyzed in this report, particularly as the pattern reflects (1) the tectonic framework of the Colorado Plateau, and (2) potential loci of entrapment of oil and gas pools. Like other states, Arizona is feeling the "energy crunch." It is hoped that the structure map of folds and the perspective for analysis contained herein might serve as a guide to further assessing Arizona's energy-resource potential and provide the impetus for industrial exploration of oil and gas in Arizona.

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ABSTRACT

Structural mapping and analysis of folds in Phanerozoic rocks in northern Arizona, using LANDSAT-1 imagery as a base, has led to the formulation of a tectonic model useful in identifying regional fracture zones both within northern Arizona and within the Colorado Plateau as a whole. The Colorado Plateau tectonic province is cut by systematically aligned, regional fracture zones that can be discerned from the monoclinial-fold pattern. Monoclines within the province have developed as a response to differential movements of basement blocks along high-angle faults. Because each monocline is the upper-crustal expression of discrete basement-fracture zones, the monoclinial-fold pattern, in total, records the position and trend of many elements of the regional fracture system. In specific, the monoclines disclose four regional fracture sets whose orientations are N. 20° W., N. 55° W., N. 20° E., and N. 55° E. Numerous zones have been identified, and their traces range in length from 100 to 600 km, averaging approximately 350 km. Spacing between adjacent fracture zones is approximately 45 km.

The regional fractures are narrow zones of concentrated strain that serve to subdivide the Plateau into a mosaic of crustal blocks. Zones of convergence of monoclines and abrupt changes in trend of the axial traces of monoclines are recognized as plan-view expressions of the corners of the basement blocks. The blocks themselves are complex polyhedra whose steeply dipping faces correspond to major fracture zones. Igneous (and salt) diapirs have been emplaced into many of the designated zones of crustal weakness. As loci of major fracturing, folding, and probably facies changes, the fracture zones have exerted control(s) on the entrapment of oil and gas.

INTRODUCTION

Background and Objectives

During 1974 the American public became acutely aware of its dependence on energy resources, particularly the fossil fuels. With the advent of awareness of the "energy crisis," certain organizations and individuals within Arizona expressed renewed interest in the need to identify more specifically the State's potential for oil and gas resources. This study is one outgrowth of that expressed concern. It represents one of several interdependent preliminary steps in evaluating Arizona's non-renewable energy-resource potential. A major purpose of this study was to delineate on a single map (see Plate I, by Davis and Kiven) the distribution and geometry of large-scale folds within the Colorado Plateau tectonic province of Arizona, with the knowledge that the resultant pattern might serve as a guide to potential loci of oil and gas entrapments. Folds, particularly domes and anticlines, are well known to provide excellent structural controls for the concentration of oil and gas. The complete designation of all large-scale folds within sedimentary rocks in Arizona has the practical merit of identifying individual structures which, in association with a suitable assemblage of lithologically favorable petroliferous sedimentary rocks, might serve as exploration targets for oil and/or gas.

In this study the structural geology of the Colorado Plateau tectonic province of Arizona was examined because the known oil and gas pools in Arizona lie within that province. Future work should be directed toward analysis within the more complexly deformed Paleozoic/Mesozoic sedimentary rocks in southern Arizona.

Methods

The methods employed in this study chiefly include: (1) LANDSAT-1 imagery analysis, (2) regional geologic mapping using LANDSAT-1 imagery as a 1:500,000 base for control and perspective, and (3) compilation of published data. In addition, simple laboratory deformational experiments were conducted in order to provide insights regarding variations in fold profiles with depth.

LANDSAT-1 imagery analysis was conducted in the spring of 1974 and involved the inspection of black and white Band 7 prints for the presence of photogeologic lineaments of possible tectonic significance. Specifically, an attempt was made to define lines or zones which reflect positions of hinges of major folds, particularly monoclinial folds (see Figure 1, p. 7). The photogeologic linears were recognizable as (1) zones of anomalously steeply dipping strata, (2) long, straight-lined stream segments, (3) straight-lined or systematically curvilinear hill slope segments, and (4) zones marked by differential incisement of drainages. The ground expression of most of the photogeologic linears recognized proved to be (1) breached monoclinial hinge zones, (2) faulted monoclines, (3) faults, and (4) margins of mesas. The first three of these have direct tectonic significance; the fourth is a geomorphic expression commonly lacking an observable, direct relationship to deformation by folding or faulting.

Using photogeologic analysis alone, it proved to be impossible to interpret unequivocally the specific type of geologic situation manifested in each of the photogeologic linears. In particular, without referring to published geologic maps, it was not possible to specify which of the many linears were indeed expressions of monoclinial folds. It also became evident during the photogeologic analysis that broad, open folds characterized by gentle limb dips (less than 5 degrees) had no appreciable photogeologic expression.

As a result of the photogeologic analysis, monoclines were singled out as the only fold-type in the Colorado Plateau province of Arizona that could be defined accurately through reconnaissance structural mapping using LANDSAT-1 imagery as a base for control. Other large-scale folds are so broad and gentle that they are essentially invisible on LANDSAT-1 imagery and impossible to place accurately in the field without detailed geologic mapping. The expression of most of the monoclines is clear both in the field and on LANDSAT-1 photos because of profound rotation of the middle limbs of these folds. However, since the monoclines grade locally into faults along common "lines" of structural weakness, photogeologic analysis alone could not be used to define explicitly the full, detailed extent of the folds.

In carrying out field investigation of the monoclinal folds, LANDSAT-1 imagery was a valuable base on which to work. Individual roads and highways, drainages, physiographic features, miscellaneous cultural features, and vegetation patterns provided reference for readily and accurately plotting positions of folds and data stations. Additionally, the strong photogeologic expression of "potential" monoclines served to delimit critical areas for study within the 35,000 square-mile region. The small scale of LANDSAT-1 imagery (1:500,000) coupled with the large area encompassed by each sheet (approximately 12,000 square miles) served to focus regional tectonic relationships. Furthermore, the lack of distortion in the LANDSAT-1 imagery permitted a quick, reliable transfer of the carefully collected and plotted data to a topographic map of the same scale.

The final step in the compilation of the structure map (Plate I) consisted of the transfer of the axial traces of folds and additional orientation data from previously published large-scale maps to the 1:500,000 topographic base. Data from approximately 40 geologic maps were transferred. Reliability of the fold relationships expressed on the previously published maps could not be tested in any meaningful way. The problem of positioning broad, gentle folds is difficult, and it is probable that a

number of folds shown may be mislocated by as much as 2 miles and incorrectly oriented by as much as 15° . To minimize error, only those folds that were documented by attitude measurements were incorporated in the final structure map included with this report.

The compilation included, as an integral part, the transfer of representative bedding attitudes, just as the field work for this study involved systematic measurement of bedding data along the monoclines. Commonly, regional structure maps do not include strike and dip readings for bedding; yet such readings provide a readily appreciated guide to the breadth, structural relief, and tightness of the folds.

The fold pattern that emerged from the application of the above-mentioned methods is essentially that displayed on existing small-scale structure maps of all or portions of the Colorado Plateau tectonic province of Arizona (e. g., Kelley, 1955b; Kelley and Clinton, 1960; Scurlock, 1967; Peirce and others, 1970). It is hoped that the utility of the map compiled in this study lies in detail made possible through (1) the availability of LANDSAT-1 imagery, (2) the published records of previous workers, (3) field studies specialized in the sense that folds were the chief focus of study, and (4) the inclusion of bedding data.

ACKNOWLEDGEMENTS

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J. N. Conley, Director of the Geology Section of the Arizona Oil and Gas Conservation Commission, initially recommended that a large-scale-fold analysis be carried out in northern Arizona and brought to my attention pertinent geologic information throughout the project. His careful and wise editing have improved significantly the quality of the manuscript and maps. K. E. Foster, Assistant Director of the Office of Arid Lands Studies, was instrumental in establishing financial support for the project and served as a coordinator between the various agencies and organizations involved in the project.

My special thanks are extended to C. W. Kiven of the Department of Geosciences who, for several months, was engaged in the enormous task of mapping the structural geology of monoclines within all of northern Arizona. P. Anderson and S. B. Keith, also in the Department of Geosciences, assisted in aspects of the project dealing with photogeologic interpretation and experimental deformation, respectively. C. E. Druitt, staff geologist for the Arizona Oil and Gas Conservation Commission, read the manuscript and provided helpful suggestions for its improvement.

Finally I am indebted to V. C. Kelley of the University of New Mexico and the thoroughness of his tectonic investigations of the Colorado Plateau. I am grateful for the use of his tectonic maps and the opportunities to discuss with him aspects of the structural framework of the Plateau.

MONOCLINES

Form

Monoclines are "narrow persistent downbends" (Kelley, 1955a, p. 799) of sedimentary strata which are particularly abundant in the Colorado Plateau tectonic province of the western United States. In fact, the current usage of the term "monocline," as noted by Kelley (1955a), was introduced to the literature by John Wesley Powell (1873; 1875), based on his geologic observations in Utah and Arizona during the 19th century. Monoclines display subhorizontal "upper" and "lower" limbs which are separated by relatively short, gentle to steep-dipping middle limbs (Figure 1). The lower hinge zones of monoclines tend to be sharper and less rounded than the upper hinge zones. The hinges of monoclines are seldom perfectly straight; rather they tend to be gently curvilinear to strongly sinuous. Locally, the monoclinial folds branch and split.

Monoclines are enormous, ranging up to 300 miles in length and commonly displaying structural relief measurable in thousands of feet. They are singularly important regional structural elements because (1) they commonly mark the boundaries between uplifts and adjacent basins, and (2) they display a structural relief which is 5 to 10 times greater than that expressed within the adjacent uplifts and basins (Kelley, 1955a, 1955b). The spatial relationship of monoclines to the distribution of uplifts and basins clearly reveals that the monoclines are fundamental zones of weakness within the Colorado Plateau (Figure 2).

Where excellent three-dimensional exposures of monoclines permit, the monoclines can be seen to be associated with and/or project downward into high-angle reverse faults (Maxson, 1961; Huntoon, 1969, 1974).

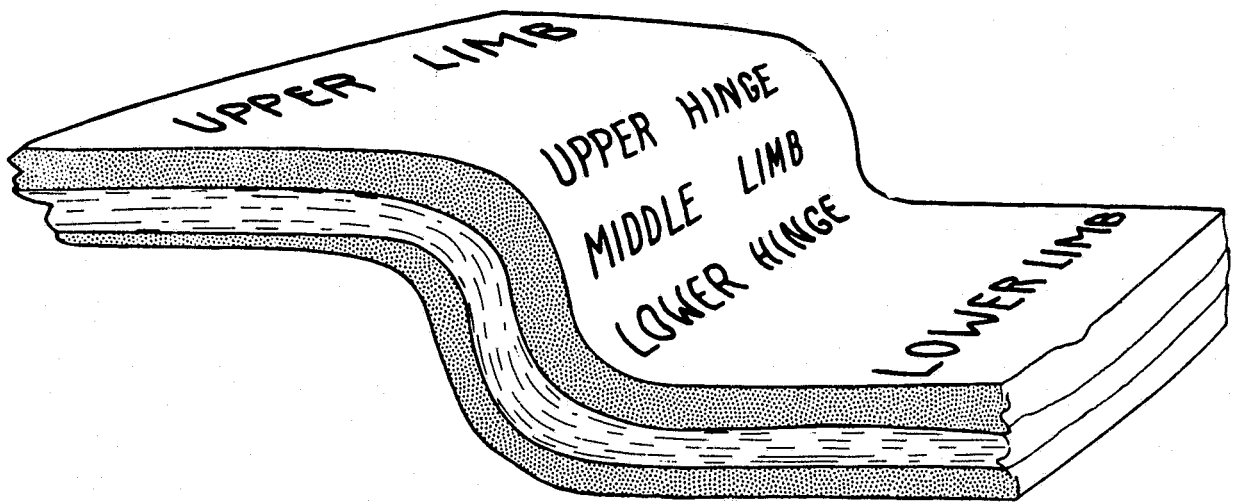


Figure 1. Schematic diagram of an idealized monoclinial fold.

BASINS

B = Blanding
BM = Black Mesa
H = Henry
K = Kaiparowits
P = Piceance
SJ = San Juan
U = Uinta

UPLIFTS

CC = Circle Cliffs
D = Defiance
DG = Douglas
E = Elk
EC = Echo Cliffs
G = Gunnison
K = Kaibab
M = Monument
N = Nacimiento
SR = San Rafael
U = Uinta
UN = Uncompahgre
WR = White River
Z = Zuni

MONOCLINES

bc = Book Cliffs
cp = Coconino Point
cr = Comb Ridge
cs = Cow Springs
dr = Davis Ranch
e = Escalante
ec = Echo Cliffs
ed = East Defiance
ek = East Kaibab
g = Grand
gv = Grandview
h = Hogback
i = Ignacio

l = Lukachukai
n = Nutria
na = Nacimiento
or = Organ Rock
r = Rattlesnake
rd = Redlands
rl = Red Lake
sj = San Juan
sr = San Rafael
u = Uncompahgre
uv = Upper Valley
w = Waterpocket
wd = West Defiance

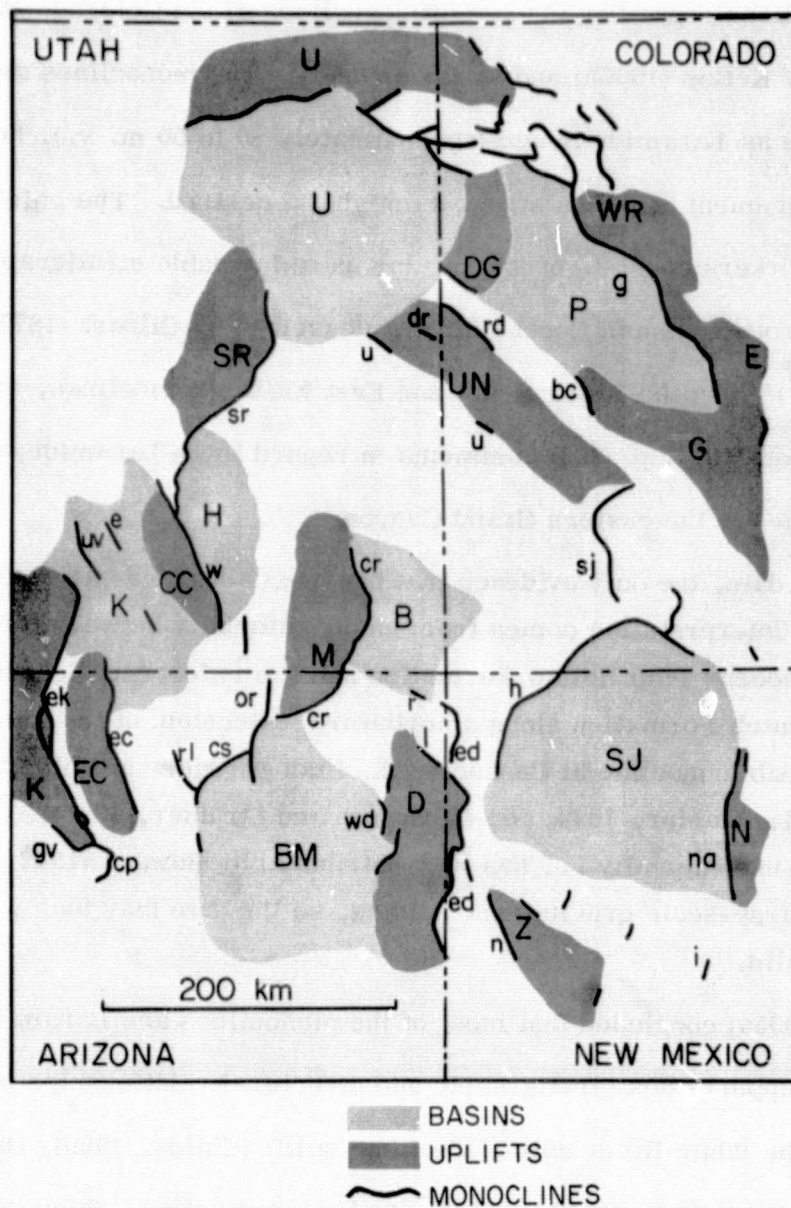


Figure 2. Map showing the distribution of basins, uplifts, and monoclines within the Colorado Plateau, from V. C. Kelley (1955b).

Time of Formation

Interpretations regarding the age of monoclines of the Colorado Plateau have been reviewed by Kelley (1955a) and Huntoon (1974). The monoclines are regarded by most workers as Laramide in age (approximately 80 to 50 m. y.), but the evidence for this age assignment is not as strong as might be desired. The chief evidence cited by most workers consists of the angular unconformable stratigraphic relationships between "late Cretaceous and Eocene Strata" described by Gilbert (1877) and Gregory and Moore (1931) along the Waterpocket and East Kaibab monoclines, respectively. However, Huntoon (1974, p. 323) comments in regard to the Laramide age assignment for the monoclines in the eastern Grand Canyon:

"To date, the only evidence that has been advanced to support this interpretation comes from an unconformity between the Paleocene Pine Hollow Formation and the Paleocene-Eocene Wasatch Formation along a northward extension of the East Kaibab monocline at Canaan Peak, Utah (Gregory and Moore, 1931; Strahler, 1944; and Babenroth and Strahler, 1945). The unconformity ... has been attributed by Bowers (1972) to large-scale gravitational sliding, so the date may be invalid."

Kelley (1955a) concluded that most of the monoclines are Laramide products, and by way of support cites stratigraphic and structural relationships observed in the vicinity of the White River uplift, the Uinta uplift (Childs, 1950), the Defiance monocline, the Nacimiento uplift, and the Hogback monocline. Barnes (1974, p. 446) suggested on the basis of detailed investigations in the Gray Mountain area, "that the major monoclinal uplifts, while presumably early Tertiary, are by no means synchronous." Further, he believes that some monoclinal folding may be as young as Pliocene (Barnes, 1975, pers. comm.).

Origin

Differences exist among the genetic models proposed for the origin of monoclines. Powell (1873, 1876), Gilbert (1875), Dutton (1880), Walcott (1890), and Nevin (1949) interpreted the monoclines as products of the draping of near-surface strata over deep-seated high-angle faults; vertical forces were considered to be responsible for the movements. Baker (1935) postulated that the monoclines formed above deep-seated thrust faults in a stress field characterized by horizontal compression. Kelley (1955a, 1955b) also favored the concept that horizontal compression was the "dominating action" in the formation of the large monoclines. Noble (1914), Maxson (1961), and Huntoon (1969, 1971, 1974, 1975), based on their work in the Grand Canyon, observed that the monoclinical folds in that region commonly are associated with reverse faulting along reactivated Precambrian high-angle faults. Based in part on such relationships, these workers postulated that monoclinical folds are products of horizontal compression. Woodward (1973, p. 97) attributed the development of monoclines to "primary horizontal compression deep within the crust" resulting in "local secondary stress fields near the surface having strong vertical components." Barnes and Marshall (1974) envision the formation of monoclines to have involved a step-like faulting of the basement and the synchronous development of a curved principal stress trajectory in the supracrustal rocks, resulting in flexural folding of the sedimentary layers. The dynamic aspects of their model are based on the analytical and experimental work of Sanford (1959).

In spite of differences that are implicit in the various dynamic models proposed for the origin of monoclines, most workers have concluded that the folds, at their present levels of exposure, are expressions of differential vertical movements along high-angle faults. Lucchitta (1974, p. 348) states, "The association between monoclines and faults suggests that the monoclinical flexures are the surface expression of zones of weakness in the competent basement ... The antiquity and repeated

reversal of movements on faults, as well as the association of monoclines with faults at depth, are well documented for the Grand Canyon." Huntoon (1974, p. 323) suggests that "the sinuosity and branching that are characteristic of the monoclines in the eastern Grand Canyon result from pre-existing trends of the Precambrian faults that were rejuvenated as the monoclines developed."

Observations by this worker of the monoclines in the Colorado Plateau tectonic province of Arizona are consistent with the kinematic generalization that monoclines are the upper-crustal expression of high-angle faults. Certainly the faults that are associated with the middle limbs of monoclines in Arizona are high-angle. Exceptions are gravity-glide phenomena, such as those found in the Gray Mountain area (Barnes, 1974) and in the middle limbs of the Red Lake, West Defiance, and Comb Ridge monoclines. The range of dip-magnitude of the middle limbs of monoclinial folds observed in Arizona implicitly suggests that the faults associated with the monoclines are high-angle. In few areas are the middle limbs overturned, and, where overturning is observed, it is only by small amounts (less than 5 or 10 degrees). Further, the middle limbs seem to be related systematically in dip-angle to proximity to basement rock. The Hunters Point (Figure 3 and 4) and Black Creek segments of the East Defiance monocline are vertical and, at those sites, the distance to basement is less than several hundred feet. In contrast, monoclines in Arizona involving Mesozoic beds, separated from basement by the entire Paleozoic section, seldom have middle-limb dip-angles greater than 45 degrees. This geometric pattern is consistent with flexural-slip and flexural-flow monoclinial folding over basement blocks differentially uplifted along high-angle faults.

The inferred kinematics of development of monoclines were modeled experimentally in order to visualize more clearly the variation in the form of such structures with depth. Guided by the basic genetic model outlined above, a sequence of "basement rocks" and overlying "sedimentary strata" was fashioned from pine 2" x 8" and

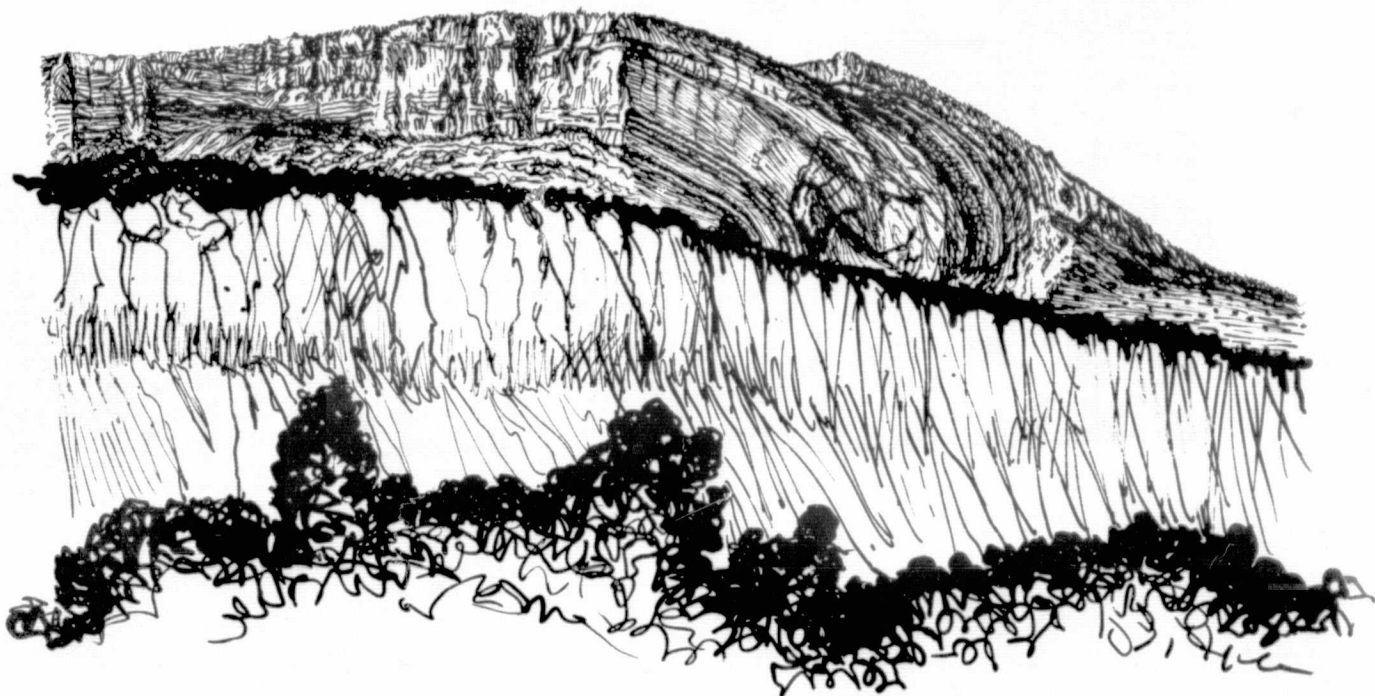


Figure 3. Tracing of a photograph of the Hunters Point segment of the East Defiance monocline; view to the northwest.

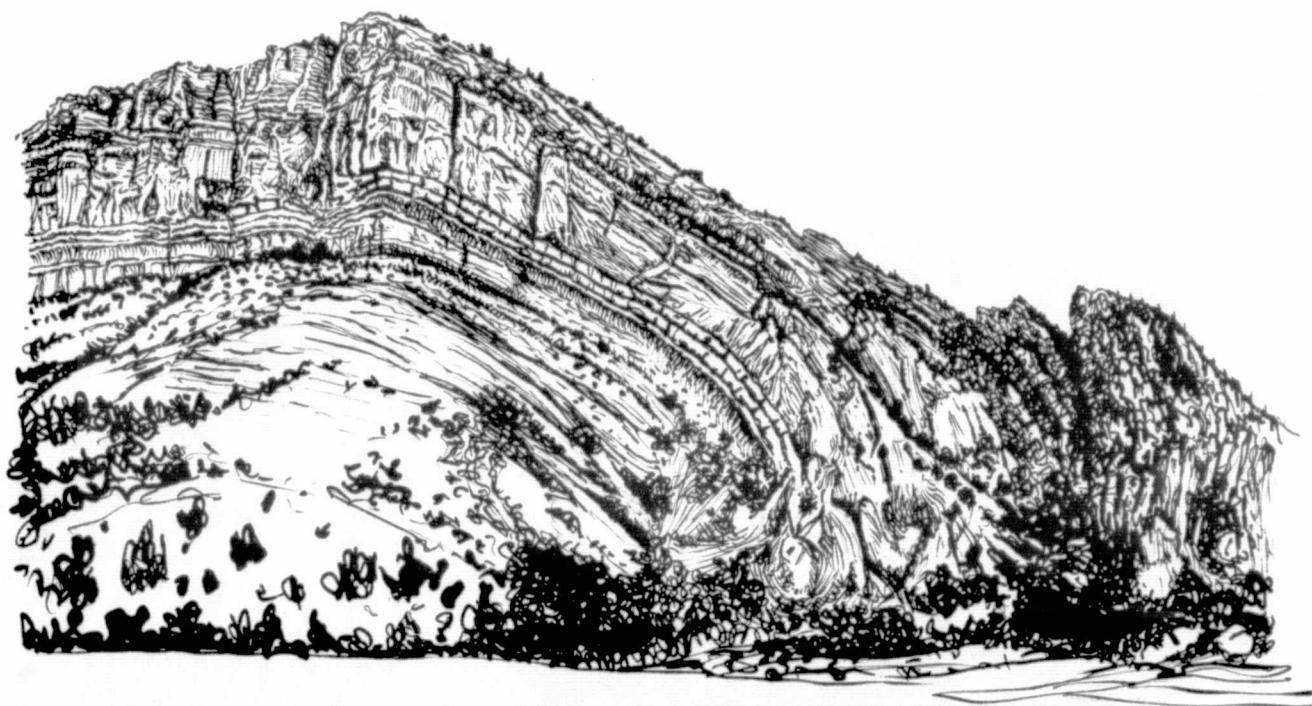


Figure 4. Closer view of the Hunters Point segment of the East Defiance monocline showing vertical attitude of middle-limb strata.

alternating dry kaolinite and modeling clay, respectively (Figure 5). The pine-board basement was sawed at an angle designed to mimic that of the high-angle basement faults described by Maxson (1961). Shortening of the "basement" was achieved by reverse faulting along the suitably oriented, pre-existing "basement fault." Shortening of the "sedimentary section" was achieved by reverse movements along a zone of high-angle faults in the dry clay layers, and by monoclinal folding of the thin, modeling-clay layers. (The modeling-clay layers were too ductile to permit deformation by faulting.) During uplift the "sedimentary strata" rode on the "basement" passively and became involved in the deformation only along the narrow upward projection of the sawcut. Modeling-clay layers situated near the top of the sequence displayed monoclinal folds with gently dipping middle limbs. Modeling-clay layers close to the "basement" displayed monoclinal folds with very steeply dipping middle limbs. Had stiffer modeling-clay layers been used, those layers close to the "basement" undoubtedly would have been deformed by faulting. Although the experimentation was performed crudely and without attention to scale-model factors, the deformation style of the modeling-clay layers is consistent with the forms of the monoclines observed during the field studies.

Photogeologic Expression

The photogeologic expression of the monoclines is remarkably clear because of the distinctive physiographic appearances of the folds. Of course, those monoclines with the greatest structural relief are the most easily discerned both in the field and through photogeologic analysis. Two major physiographic classes of monoclinal expression can be distinguished. One class is characterized by the more or less complete topographic expression of the monoclinal form. Such identity of structure and topography occurs where erosion has resulted in the stripping of relatively non-resistant beds to the level of some resistant lithologic unit. The result is a stripped

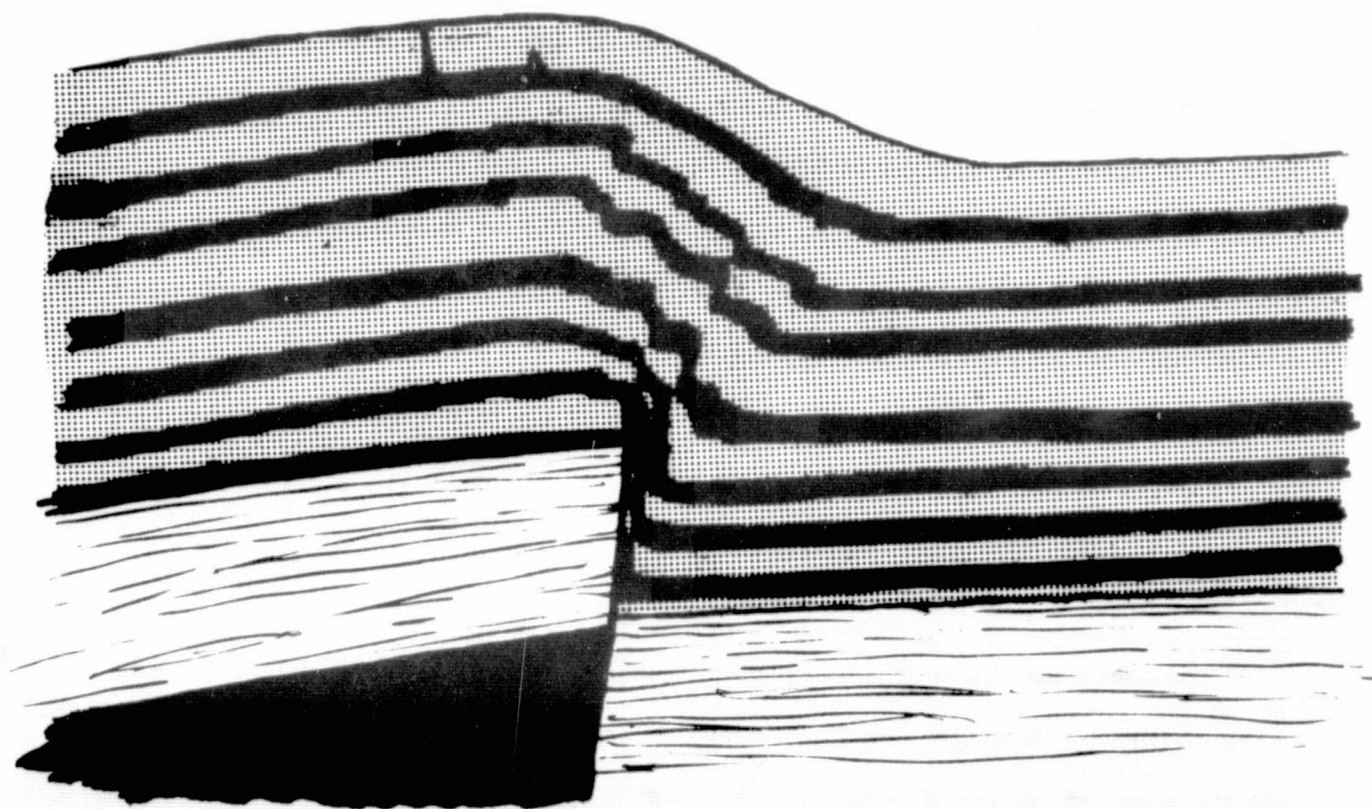


Figure 5. Photograph of experimental deformational model of "strata" of kaolinite and modeling clay resting on a rigid "basement" of pine board. Reverse faulting of basement block along a pre-cut high-angle fault produces monoclinical fold in overlying thin layers.

structural surface. Where the resistant unit is horizontal, the land surface is flat; where the resistant unit is folded into the form of a monocline, the land surface is characterized by a down-stepping of the topography along a hillslope which corresponds in position and angle-of-dip to the monocline's middle limb. This class of monoclinial expression is best developed in the Grand Canyon region where the land surface is capped by the Kaibab Limestone of Permian age. There, hillslopes correspond, almost without exception, to the middle limbs of monoclines (Figure 6). Such hillslope segments are typically quite narrow (less than 5 miles) and are relatively deeply incised by numerous, closely spaced stream channels. Another excellent example of the identity of topography and structure is provided by the Houck monocline (Figure 7) on the southwest side of the Defiance uplift (see Plate I). In areas where this class of monoclinial expression prevails, the middle limbs of the monoclines can be accurately mapped on LANDSAT-1 imagery by simply tracing out the narrow, curvilinear hillslope zones which are marked by an anomalously close spacing and deep incisement of stream channels. Examples include the East Kaibab, Grandview, Coconino Point, and Additional Hill monoclines in the vicinity of Gray Mountain (Figure 8 and Plate I).

A second physiographic class of monoclinial expression is characterized by long, narrow, curvilinear to sinuous ridges which contrast markedly with the adjacent broad flat surfaces so typical of the Colorado Plateau. The ridges are the expression of resistant, moderately to steeply dipping middle-limb strata of breached monoclines (Figure 9). The Echo Cliffs and Comb Ridge monoclines (Plate I) are excellent examples of this form of physiographic expression.

Pattern

The monoclinial fold pattern in northern Arizona within the Colorado Plateau tectonic province is shown in Plate I. The basic monoclinial fold pattern has been known for some time, due to careful mapping and/or compilation by many previous

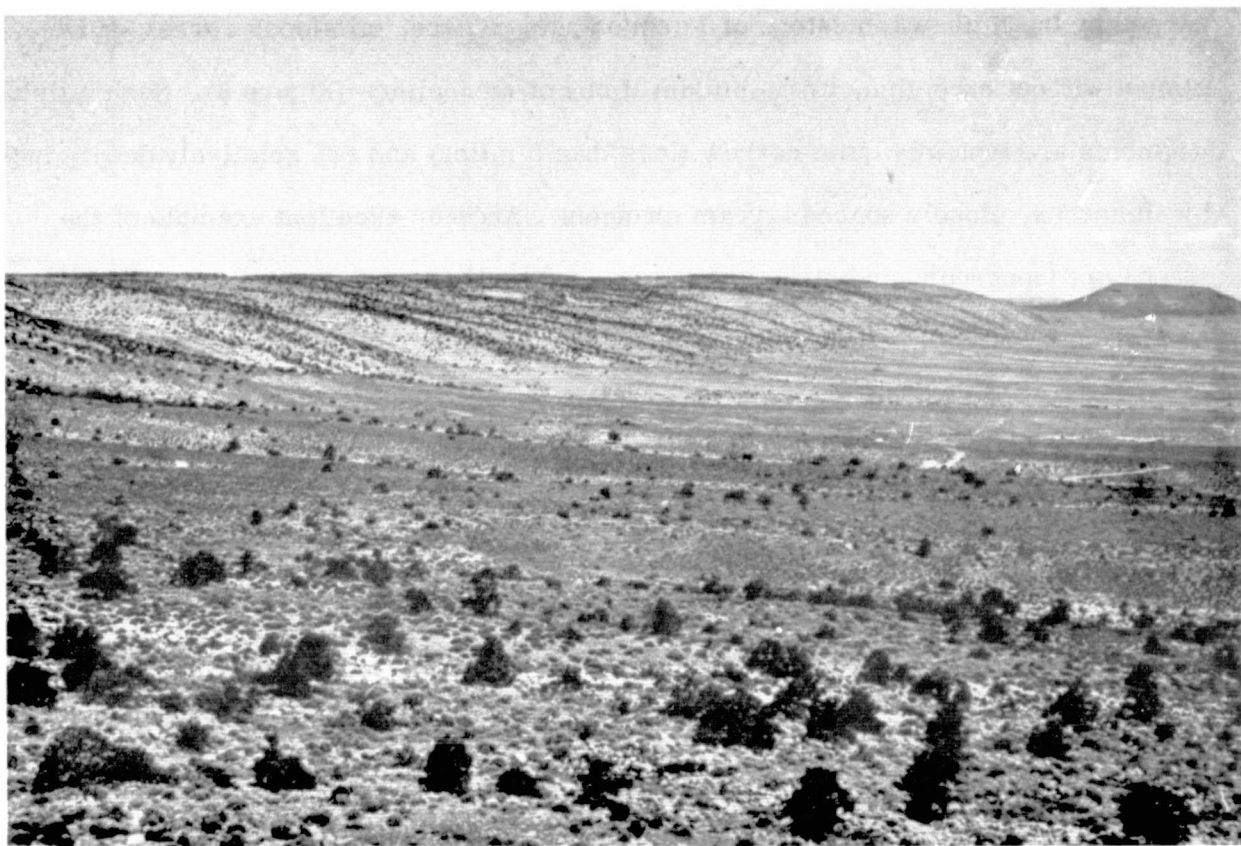


Figure 6. Photograph showing the physiographic expression of a portion of the East Kaibab monocline. Hillslope corresponds to the middle limb of the fold.

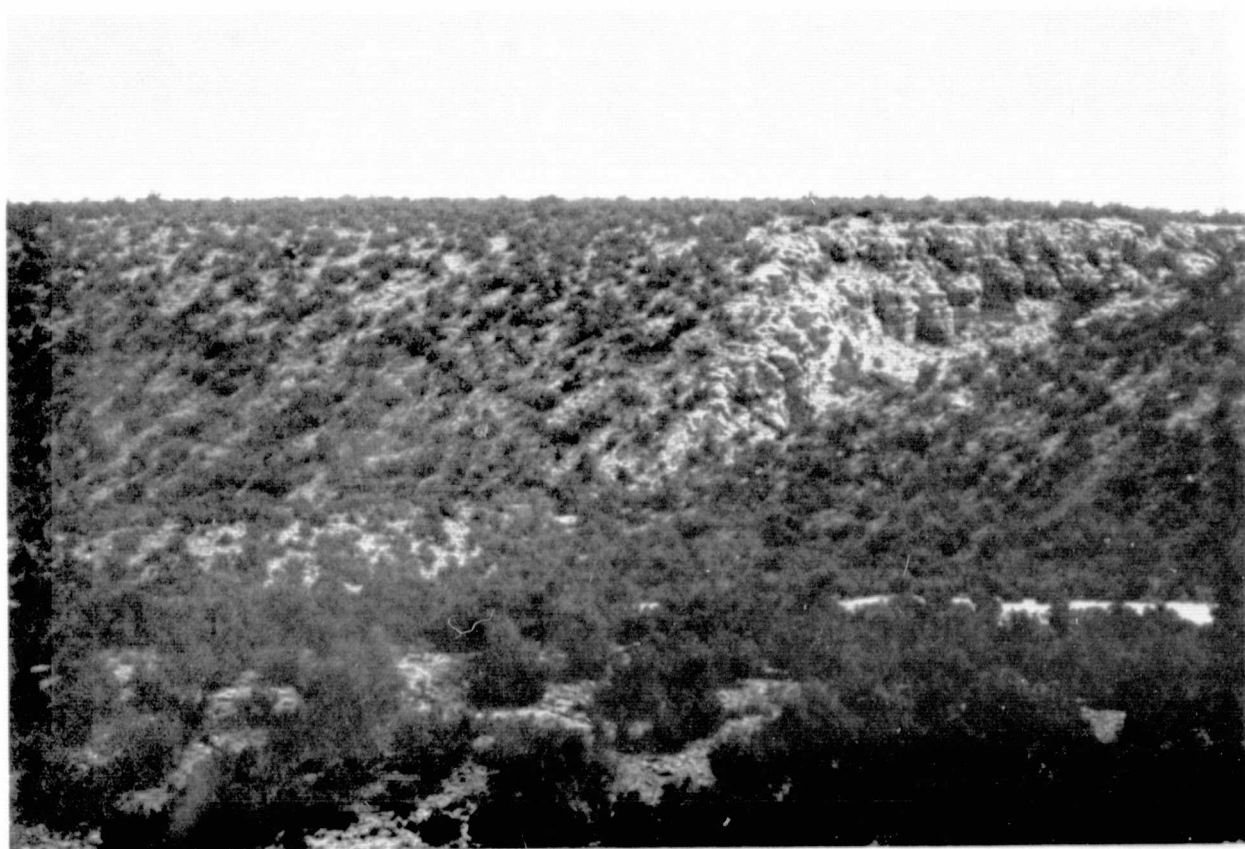


Figure 7. Photograph showing the physiographic expression of a portion of the Houck monocline. Hillslope corresponds to the middle limb of the fold.

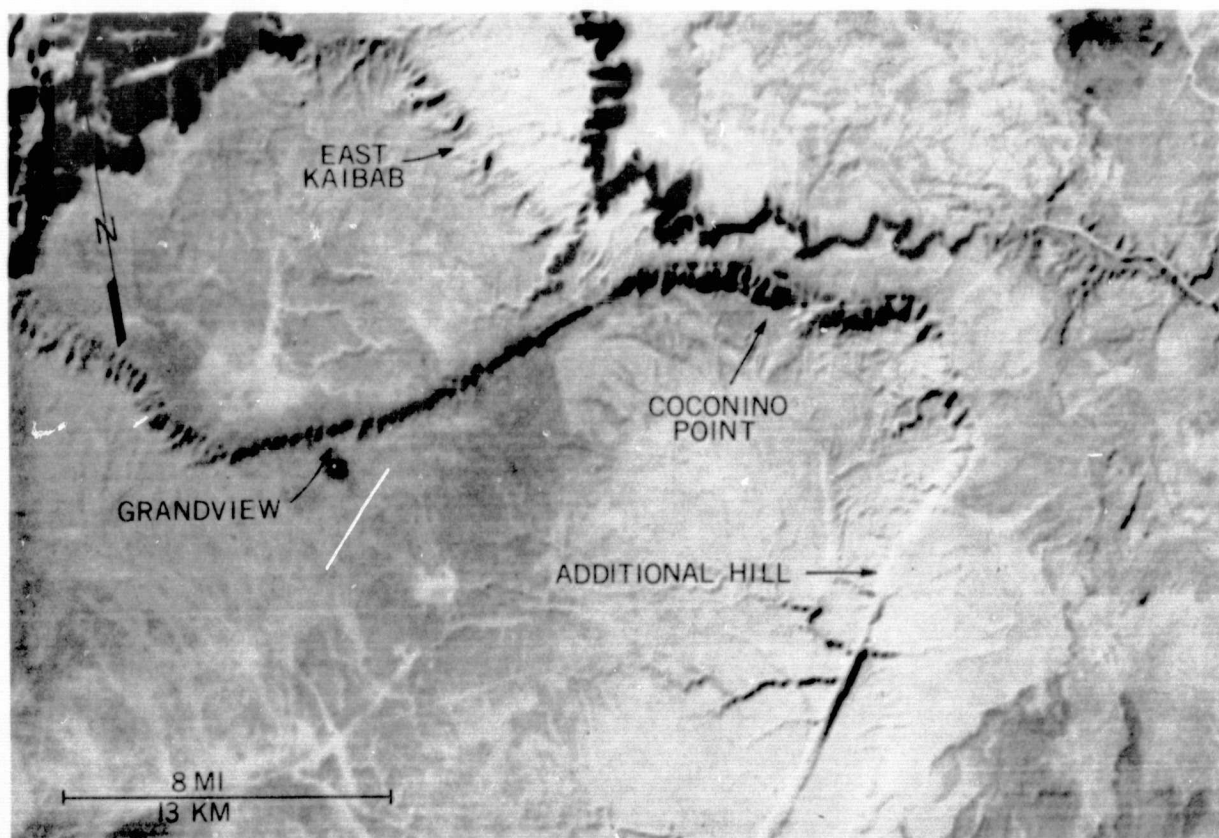


Figure 8. Photogeologic expression of the interference of the East Kaibab, Grandview, Coconino Point, and Additional Hill monoclines in the vicinity of Gray Mountain (approximately 45 miles north of Flagstaff) as revealed in LANDSAT-1 imagery.



Figure 9. Photograph of the east-dipping middle-limb strata of the breached Echo Cliffs monocline. View toward the northeast.

workers (e.g. Babenroth and Strahler, 1945; Akers and others, 1962; Wilson and others, 1960; Moore and others, 1960; Maxson, 1961, 1967a, 1969; Cooley and others, 1969; Kelley 1955a, 1955b; Kelley and Clinton, 1960; Scurlock, 1967; Peirce and others, 1970; Doeringsfeld and others, 1958, etc.). However, the structure map included with this report may represent in some ways a refinement in that (1) the traces of both the upper and lower hinge zones of the monoclines are presented, (2) the positioning of the axial traces of the folds is generalized as little as possible, and (3) attitude data for upper, middle, and lower limbs are generously supplied. Furthermore, the use of a LANDSAT-imagery mosaic as a base provides added perspective regarding the geomorphic expression of the major structures.

All of the monoclines represented on the structure map involve Paleozoic and/or Mesozoic sedimentary strata. In fact, at the present level of exposure in the Colorado Plateau of Arizona, most of the monoclines are developed in late Paleozoic and Mesozoic rocks. For example the monoclines in the Grand Canyon region are optimally displayed by the form of the Permian Kaibab Limestone; the monoclines on the east and west flanks of the Defiance Uplift are expressed at the surface by rocks which range in age from Pennsylvanian through Cretaceous. Near the Monument Valley the monoclines are revealed at the surface in strata of Triassic age. Although stratigraphy is not conveyed on the structure map, the distribution of stratigraphic systems is available on the Geologic Map of Arizona (Wilson and others, 1969) which, like the structure map, is scaled at 1:500,000.

Several factors may be responsible for the apparent absence of monoclinal folds in major portions of the Colorado Plateau tectonic province of Arizona. In northwestern Arizona the absence of major monoclines might be attributable to a relatively close proximity to basement rocks combined with the massive character of the Paleozoic rocks. The major mode of deformation was by faulting, not folding. Within the south-central portion of the Colorado Plateau tectonic province in Arizona,

great expanses are covered with Cenozoic volcanic rocks which serve to cover any monoclinial structures which might otherwise crop out. Within the Black Mesa basin there is a great thickness of Mesozoic strata. Given the concentric, parallel geometry of monoclinial folds, it is probable that any major monocline at depth in the basin would gradually die out before reaching the present level of exposure. In summary, it would seem that the formation of monoclines is dependent in a sensitive way on (1) the capacity of stratigraphic units to fold and (2) the distance above faulted basement blocks. As a consequence, optimum development of monoclines in the Colorado Plateau tectonic province of Arizona is perceived by this worker to be restricted to a relatively narrow stratigraphic interval.

The map pattern of monoclines in northern Arizona is multi-directional, sinuous, and branching (Plate I). Three distinct directional groupings of monocline trends are recognizable: NNW, NE, and north to NNE. The NNW-trending monoclines are the most dominant and are represented by approximately 250 miles of cumulative axial length. The NNW-trending monoclines include major segments of the East Kaibab, Echo Cliffs, and East Defiance monoclines as well as the Red Lake, Crazy Jug, and Oraibi monoclines. The NNW-trending set of monoclinial folds are asymmetric in an easterly direction (i.e. the middle limbs dip east). The NE-trending monoclines include segments of the Grandview, Coconino Point, Black Point, Cow Springs, Comb Ridge, and West Defiance monoclines. Their cumulative length is approximately 110 miles. With the exception of the segments of the West Defiance and Grandview monoclines, these NE-trending monoclines are asymmetric to the southeast. The north to NNE-trending monoclinial segments include portions of the West Kaibab, East Kaibab, Echo Cliffs, Organ Rock, West Defiance, and East Defiance monoclines. With the exception of the West Kaibab and West Defiance structures, asymmetry of these north to NNE-trending structures is easterly.

The sinuosity of the monoclines is conspicuous and has been discussed by many previous workers (e.g. Kelley, 1955b; Huntoon, 1971). The East Kaibab

monocline is systematically curvilinear, a composite of NNW- and NNE-trending segments (Plate I). The Echo Cliffs monocline is comprised of two NNW-trending segments connected by a relatively short NNE-trending segment. The East Defiance monocline displays the most extreme sinuosity; its form has been described in detail by Kelley (1967).

Locally, the monoclines in northern Arizona are seen to branch and split. At junctures of converging monoclines or monoclinial splays, relatively complex structural relationships are evident. Such complications include (1) the structural terraces along the East Kaibab monocline (Babenroth and Strahler, 1945), (2) the fold interference patterns at Gray Mountain, the locus of convergence of the Grandview, East Kaibab, Coconino Point, and Additional Hill monoclines (Barnes, 1974), (3) the convergence of the Red Lake and Cow Springs monoclines near Tonalea, and (4) the "wishbone junction" of the Comb Ridge, Organ Rock, and Cow Springs monoclines near Kayenta (Plate I).

The major monoclines in northern Arizona occupy critical structural positions with respect to the distribution of tectonic subprovinces within the Colorado Plateau. This is explicit in V. C. Kelley's tectonic subdivision of the Colorado Plateau in which monoclines commonly mark the boundaries between adjacent, structurally distinctive, subprovinces (Kelley, 1955b; Kelley and Clinton, 1960) (Figure 2, p. 9). Based on the magnitude of structural relief and total length, the major monoclines in northern Arizona, from west to east, include the West Kaibab, East Kaibab, Grand View-Coconino Point, Echo Cliffs, Red Lake, Cow Springs, Organ Rock, Comb Ridge, West Defiance, and East Defiance (Plate I). Of these, the West and East Kaibab monoclines mark the west and east margins, respectively, of the imposing north-trending Kaibab uplift (structural relief approximately 3500 feet). The East Kaibab and Echo Cliffs monoclines form the west and east boundaries, respectively, of the NNW-trending Echo Cliffs uplift. The polygonal Black Mesa basin is bounded

on several sides by monoclines, most notably the Cow Springs, the southern extension of the Red Lake, and the disjointed West Defiance monocline. The convergence of the Organ Rock and Comb Ridge monoclines near Kayenta delimits the SSW terminus of the Monument upwarp. The Defiance uplift, whose structural relief is approximately 6000 feet, is bounded by the West and East Defiance monoclines. The East Defiance monoclinical complex, in turn, marks the west boundary of the Gallup sag and a portion of the San Juan basin.

ANTICLINES AND SYNCLINES

The anticlines and synclines shown on the structure map included with this report have been compiled in large part from the work of others (see citations on Plate I). Excellent descriptions of specific anticlines and synclines within the Colorado Plateau tectonic province of Arizona are provided by Gregory (1917), Kelley (1958), and Kelley and Clinton (1960). No attempt will be made to summarize those descriptions; rather, general comments will be made regarding the anticlinal/synclinal fold pattern, in total.

Almost without exception, anticlines and synclines within northern Arizona are shallow-plunging, broad, open, upright folds with curvilinear traces. Most trend in a northwesterly direction, but many NE-trending folds ignore the regionally northwesterly orientation. Each of the major, relatively narrow uplifts of the Plateau (i.e., the Kaibab, Echo Cliffs, Monument, and Defiance) is surmounted by a major anticline as well as lesser anticlines and synclines which are subparallel to the trend of the uplift itself (Plate I). The uplifts may be thought of as enormous anticlines, asymmetric to the east or southeast. Each is bounded on the east or southeast by a major monocline, directly to the west of which can be delineated a major, subparallel anticlinal hinge (for example, the Kaibab, Echo Cliffs, Monument, and Defiance anticlines). Similarly, the lower hinges of the major monoclines are commonly paralleled basinward by several closely spaced upright anticlines and synclines. The Comb Ridge, East Defiance, and Organ Rock monoclines are illustrative in this regard.

In contrast to the above-mentioned anticlines and synclines which are spatially, geometrically, and, by inference, genetically related to the formation of the major uplifts and associated monoclines, a great number of anticlines and synclines within

the Colorado Plateau of Arizona are unrelated to the monoclinial fabric. Examples of this class of folds include the Tuba City-Howell Mesa syncline, the Preston Mesa-Mount Beautiful anticline, the Kaibito-Black Mesa syncline, and the Cow Springs anticline (Plate I). As represented on Kelley's (1955b) structure map of the Colorado Plateau, these folds appear to be refolded by the monoclines. For example, the NW-trending Cow Springs anticline and Kaibito and Black Mesa synclines both appear to plunge into the NE-trending Cow Springs monocline. Such relationships suggest that many of the northwesterly-trending, broad, upright folds in northern Arizona may pre-date the major monoclinial folding.

Many relatively short, northeasterly-trending anticlines and synclines have been reported by previous workers, and these are plotted on the structure map (Plate I). Examples include the Turner Springs and Winslow folds near Winslow, and the Carrizo fold near Holbrook. Like most of the anticlines and synclines in northern Arizona, these folds are open with limb dips generally less than 5 degrees.

The tightest anticlines and synclines in Phanerozoic rocks within the Colorado Plateau tectonic province in Arizona occur as cross-folds on the East Defiance monocline (Kelley, 1967) (Plate I). These folds plunge gently to moderately to the southeast and display limb dips as great as 45 degrees (Kelley, 1955b; Woodward, 1973). The largest folds of this type are located in New Mexico, but within 15 miles of the Arizona/New Mexico state boundary.

Within the extreme northeast corner of Arizona, the fold pattern is relatively complex and anomalous in trend (Plate I). Anticlines and synclines trend west-northwest, parallel to the trace of Rattlesnake monocline which borders this zone to the south. In addition, anticlines and synclines marginal to the Carrizo dome plunge radially away from the vicinity of the Carrizo igneous centers.

RELATION OF FOLDS TO BASEMENT TECTONIC FRAMEWORK

Dilemma

North-northwest, northwest, northeast, and north-to-northeast trends have been cited as representative of folding within the Colorado Plateau tectonic province in Arizona. Difficulties have been encountered by most workers in attempting to explain the diversity of trends of monoclines, anticlines, and synclines by means of a constantly oriented stress pattern transmitted through the crustal rocks. Kelley and Clinton (1960) recognized two major monoclinial fold sets (northwest and northeast) and explained the development of these sets in a two-phased Laramide deformation: "... the northeasterly trending monoclines may have formed first under the influence of a dominant regional horizontal pressure from the Central Rockies. ... the Plateau monoclines ... of northwesterly trend, may have formed slightly later during a second major phase of Laramide orogeny." (Kelley and Clinton, 1960, p. 96). They add: "In the above analysis the northerly trending ... monoclines were not mentioned. Although they might be the product of a separate diastrophic phase, it is preferable for the present to include them with the first phase. However, their relationship to the northeasterly trending monoclines is not clear." (Kelley and Clinton, 1960, p. 97).

The abrupt nature of the changes in trend of individual monoclines is impressive. The zones where the shifts in trend take place serve to connect two (or three) relatively straight monoclinial segments (Plate I). For example, approximately 45 miles NNE of Flagstaff, the axial trace of the Black Point segment of the East Kaibab monocline changes in trend from S. 35° E. to S. 30° W. Sixteen miles NNW of Cedar Ridge, the Echo Cliffs monocline abruptly shifts its axial orientation from N. 30° W. to N. 10° E. (Plate I). Near Tsegi at the SW end of the Monument upwarp, the N. 10° E. -trending Organ Rock monocline becomes the N. 45° E. -trending Cow Springs monocline.

North of Canyon De Chelly, the Sheep Creek segment of the West Defiance monocline undergoes a shift in trend of approximately 85 degrees, from N. 60° W. to N. 25° E. The most dramatic changes in monoclinial trends occur in the vicinity of Gray Mountain; these relationships have been described by Barnes (1974) and involve the Grandview, East Kaibab, Coconino Point, and Additional Hill monoclines (Plate I; Figure 8, p. 20).

Abrupt changes in fold orientation of the type described are not characteristic of systems of flexural or buckle folds in most sedimentary rock sequences. Generally, folds developing within a uniform regional compressional stress regime tend to remain constantly oriented at right angles to the direction of greatest principal stress. (Such a response to regional compression may well be represented by the Black Mesa syncline, Cow Springs anticline, Tuba City syncline, etc.). It seems unlikely that the complexities of the monoclinial fold pattern can be explained in a satisfactory manner by inferring profound changes in the principal stress configuration during the folding. If systematic superimposed fold patterns could be identified, such a dynamic model might be permissible. However, the field data clearly reveal that many individual monoclines contain genetically synchronous segments of dramatically different orientation.

Premise for Interpretation

It is probable that most of the monoclines in the Colorado Plateau developed as a response of the stratified rocks to differential vertical uplift of the Precambrian basement along reactivated, pre-existing, high-angle faults (or fault zones). The major amount of deformation of this type presumably took place during the Laramide. Assuming that each monocline is the upper-crustal expression of a discrete basement-fracture zone, it should follow that the monoclinial fold pattern, in total, is the expression of part of the Colorado Plateau basement-fracture system. Developing

this concept, abrupt changes in orientation of the axial traces of monoclines may be recognized as plan-view expressions of the "corners" of basement blocks. The blocks themselves may be viewed as complex polyhedra whose steeply dipping faces correspond to major fracture zones. Differential vertical movements involving adjacent basement blocks may produce monoclinal folding of stratified rocks higher in the crust.

Support for a basement-block tectonic model is evident in the recent contributions of a number of workers in the Colorado Plateau and the Rocky Mountains. Shoemaker and others (1974, p. 382) concluded on the basis of their analysis of the Bright Angel and Mesa Butte fault systems of northern Arizona: "Mayor (Precambrian) displacement probably occurred on a few main faults, which divide the crust into blocks tens of kilometers across ... both the major and minor faults controlled later, dominantly vertical displacement in late Precambrian and Phanerozoic time." Thomas (1974) analyzed regional lineaments in the Williston-Blood Creek basin of North Dakota and Montana and reported that the systematically arranged NE- and NW-trending lineaments are the expression of a block pattern within the basement rocks. Saunders (1975), through the study of regional lineaments in the west, concluded: The regional lineaments ... "are interpreted to represent the basic tectonic framework of North America, and are believed to be very old, i. e., Precambrian, deep-seated planes of weakness which divide the continental plate into blocks Periodic tectonic stress during geologic time has resulted in block interactions and adjustments producing geologic structures, and has, in part, controlled depositional environments." Also, Matthews and others (1975) studied folds and faults within the northern Front Range and concluded that most of the major folds were produced by a passive draping of sedimentary strata over the edges of basement blocks.

In applying the basement-block tectonic model to the analysis of monoclines, it has been assumed that each straight-line monoclinal segment represents the approximate upward projection of part of a regional basement fracture zone. By

extending the numerous straight-line monoclinial segments, the systematic nature of the inferred basement-fracture pattern of the region becomes apparent. Specific fracture-zone traces are identifiable as loci of (1) individual monoclines, (2) two or more monoclinial segments, (3) end-points of monoclinial segments, (4) abrupt changes in trend of the monoclines, and (5) zones of convergence of two or more monoclines (Figure 10).

Inferred Basement-Fracture System for the Colorado Plateau

The principles of analysis may be conveyed by considering the monoclinial fold pattern for the Colorado Plateau as a whole. Most of the monoclinial segments can be related to four fundamental inferred fracture directions which correspond to the preferred monoclinial folds trends: N. 20° W., N. 55° W., N. 20° E., and N. 55° E. Of these, the N. 55° E. trend is coincident with the NE-trending Precambrian grain (foliation, elongate massifs, etc.) within and adjacent to the Colorado Plateau (Kelley, 1955b). NE and NW trends were cited by Wise (1968) as the two major fracture directions for the Colorado Plateau. Additionally Mayo (1958), in his lineament-tectonic analysis of the Southwest, emphasized the degree to which NW and NE lineaments express the mega-fabric of the Colorado Plateau and surrounding tectonic provinces.

The inferred N. 20° W. -striking regional fracture zones are presented in Figure 11* and, for convenience, are identified by names related to local structural, or geographic, features. The Kaibab and Echo Cliffs fracture zones project through the East Kaibab and Echo Cliffs monoclines. The Lee's Ferry fracture zones passes through relatively short, northern-most segments of the East Kaibab and Echo Cliffs monoclines. The Red Lake fracture zone is the loci of the NNW-trending Upper Valley and Red Lake monoclines. The Escalante fracture zone is coincident with the Escalante monocline and the SE extension of same. The Waterpocket

*Although the inferred fracture zones are presented herein (Figures 11-15) on a very small-scale map of monoclines, the actual analysis was carried out using Kelley's (1955b) 1:1,000,000 tectonic map of the Colorado Plateau.

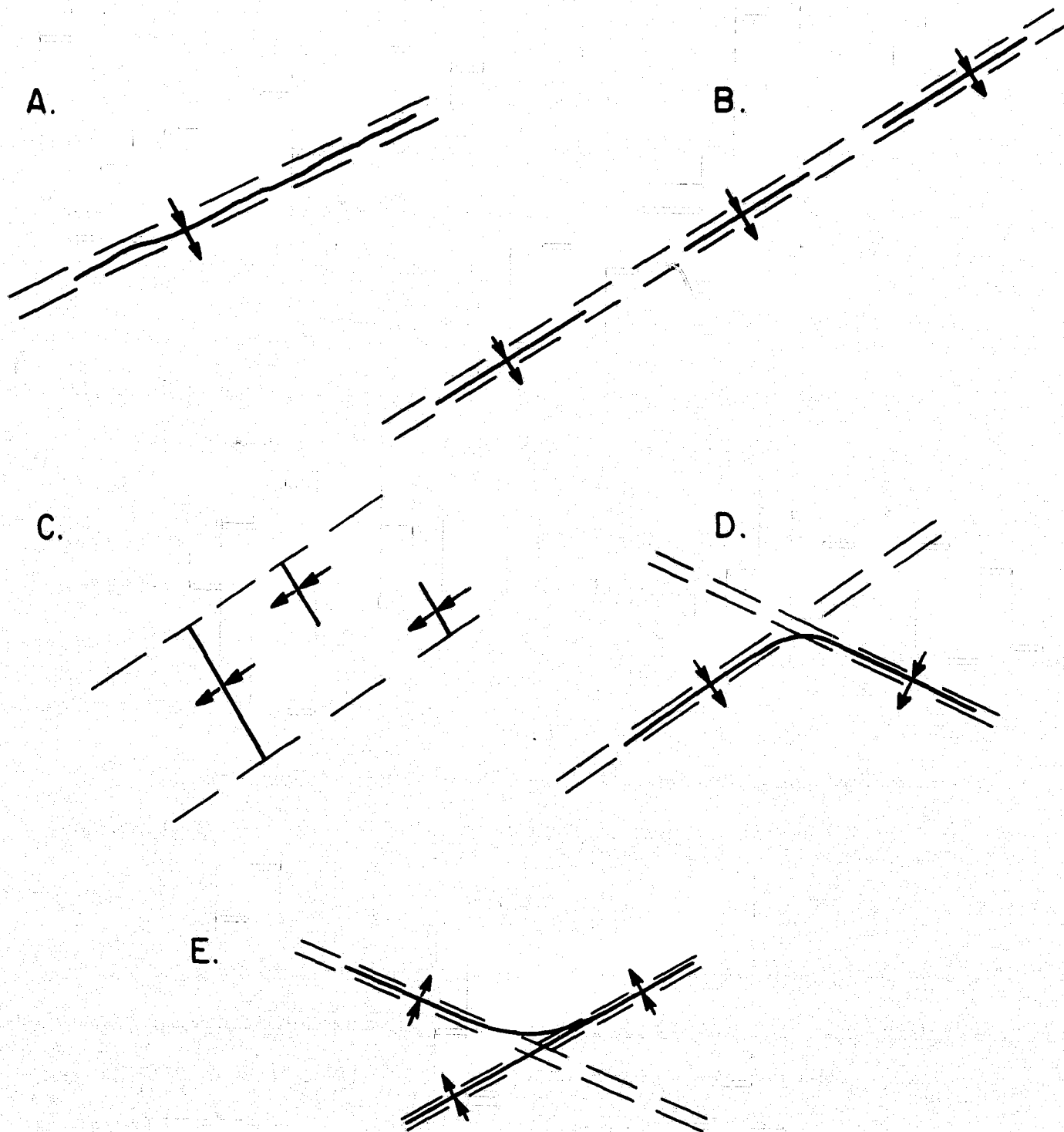


Figure 10. Examples of some of the criteria used to define the traces of inferred fracture zones. (A) monoclinal segment, (B) two or more monoclinal segments, (C) end-points of monoclinal segments, (D) abrupt change in monoclinal trend, and (E) convergence of two or more monoclines.

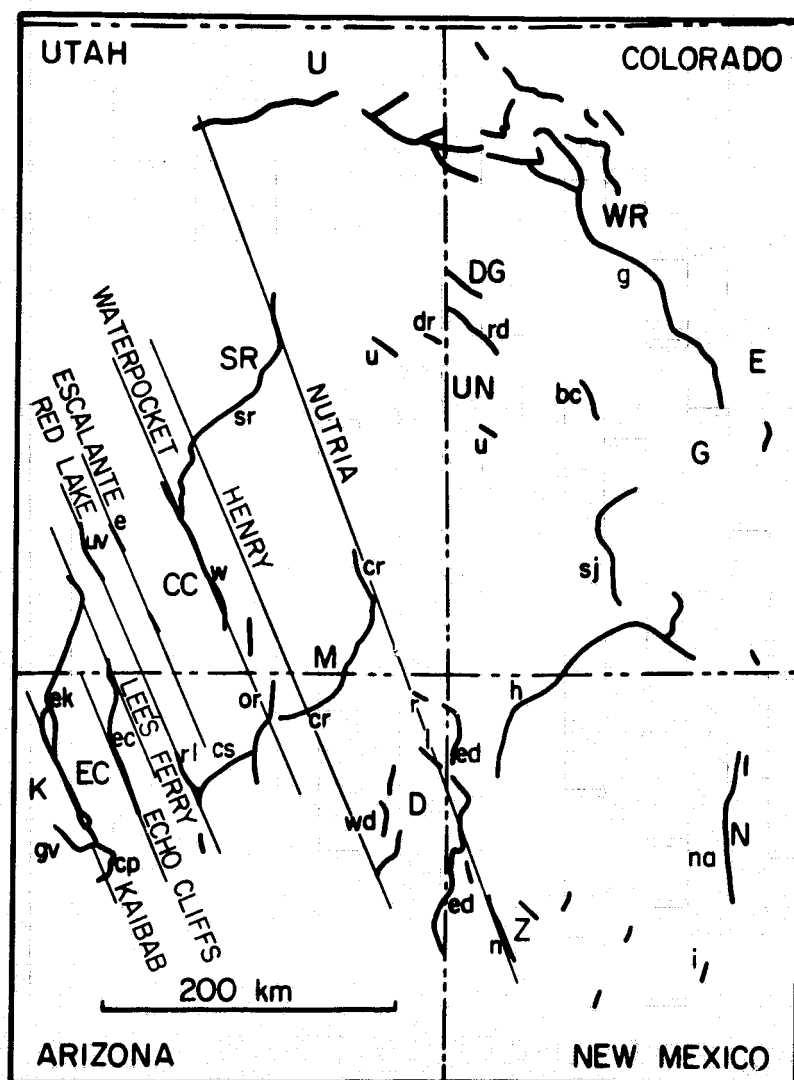


Figure 11. Map showing traces of the inferred NNW-striking fracture zones. Base map of monoclinial fold pattern from V. C. Kelley (1955b).

fracture zone parallels the east flank of the Circle Cliffs, uplift and projects SSE through the junction of the Organ Rock, Comb Ridge, and Cow Springs monoclines. The Henry fracture zone extends SSE from the marked bend in the San Rafael monocline through the SW termination (and bend) of the West Defiance monocline, although the Comb Ridge monocline between is not noticeably affected. Finally, the Nutria fracture zone is expressed by segments of the San Rafael, Comb Ridge, and Nutria monoclines; in addition, it represents the SE terminus of the Lukachukai monocline, the NW terminus of the Rattlesnake monocline, and coincides with the axial planes of cross-folds on the middle limb of the East Defiance monocline.

The so-called Nutria fracture zone corresponds to a significant lineament cited by Kelley (1955b) as separating two tectonic subprovinces within the Colorado Plateau: a southwestern subprovince, dominated by major uplifts, and characterized by NE-facing monoclines, and a northeastern subprovince containing the major basins, and characterized by SW-facing monoclines. The profound expression of the inferred NNW-striking fracture zones appears to be restricted to the southwest portion of the Colorado Plateau. With the exception of the Henry fracture zone, all are in part coincident with monoclinal segments (i. e., zones of demonstrable differential vertical movement).

Many N. 55° W. -striking fracture zones can be identified on the basis of the monoclinal fold pattern (Figure 12). In fact, the N. 55° W. tectonic trend in the Colorado Plateau was recognized and emphasized by Kelley (1955a; 1955b) and Kelley and Clinton (1960) as a major one. The Rico fracture zone is coincident with the NW-trending segment of the Hogback monocline, projecting NW through the southern terminus of the San Juan monocline and a major bend in the San Rafael monocline. Northeast of the Rico fracture zone, the La Sal, Uncompahgre, Davis Ranch, Redlands, Book Cliffs, and Grand fracture zones can be identified on the basis of N. 55° W. -trending monoclinal segments.

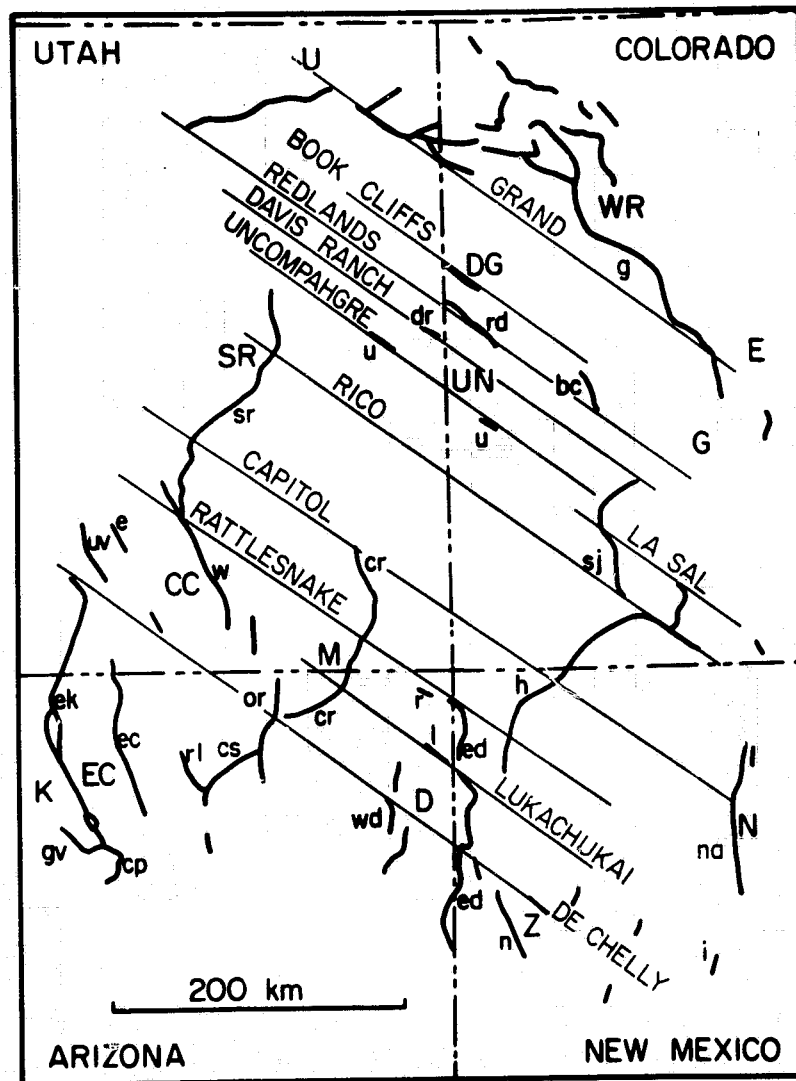


Figure 12. Map showing traces of the inferred NW-striking fracture zones. Base map of monoclinical fold pattern from V.C. Kelley (1955b).

Southwest of the Rico fracture zone, the inferred Capitol fracture zone is nowhere coincident with a monoclinal segment, but is positioned on the basis of a major bend in the San Rafael monocline, the northern terminus of the Comb Ridge monocline, and a bend in the Nacimiento monocline. The southeastern portion of this inferred zone is conjectural, especially as its crossing does not appear to affect the Hogback monocline. The Rattlesnake fracture zone projects SE from the juncture of the Waterpocket and San Rafael monoclines and coincides with the eastern terminus of the Rattlesnake monocline, and the northern-most segment of the East Defiance monocline. It does not seem to affect the Hogback monocline. The Lukachukai fracture zone includes a monocline of the same name and a NW-trending segment of the East Defiance monocline, and from there passes through a major bend in the Comb Ridge monocline. The De Chelly fracture zone is coincident with the short NW-trending segment of the East Kaibab monocline at its northern terminus, passes SE through the junction of the Organ Rock, Comb Ridge, and Cow Springs monoclines, through the NW-trending bend and break in the West Defiance monocline, and along the Pinedale monocline, the northeast boundary of the Zuni uplift. The trace of this fracture zone is similar to the Zuni lineament of Kelley (1955b). With the exception of the Capitol and Rattlesnake zones, all of the N. 55° W. -trending fracture zones are in part coincident with monoclines.

The inferred NNE-striking fracture zones are presented in Figure 13. The Kane fracture zone includes a segment of the East Kaibab monocline and marks the northwest terminus of the Escalante monocline, although its crossing does not affect the Upper Valley monocline in between. The Cedar fracture zone projects north-eastward from the bend in the Grandview monocline, through the NW terminus of a structural terrace (Cedar Mesa section) of the East Kaibab monocline, along a NNE segment of the Echo Cliffs monocline, and along the sinuous NNE juncture of the Waterpocket and San Rafael monoclines. The Dirty Devil fracture zone, dashed in

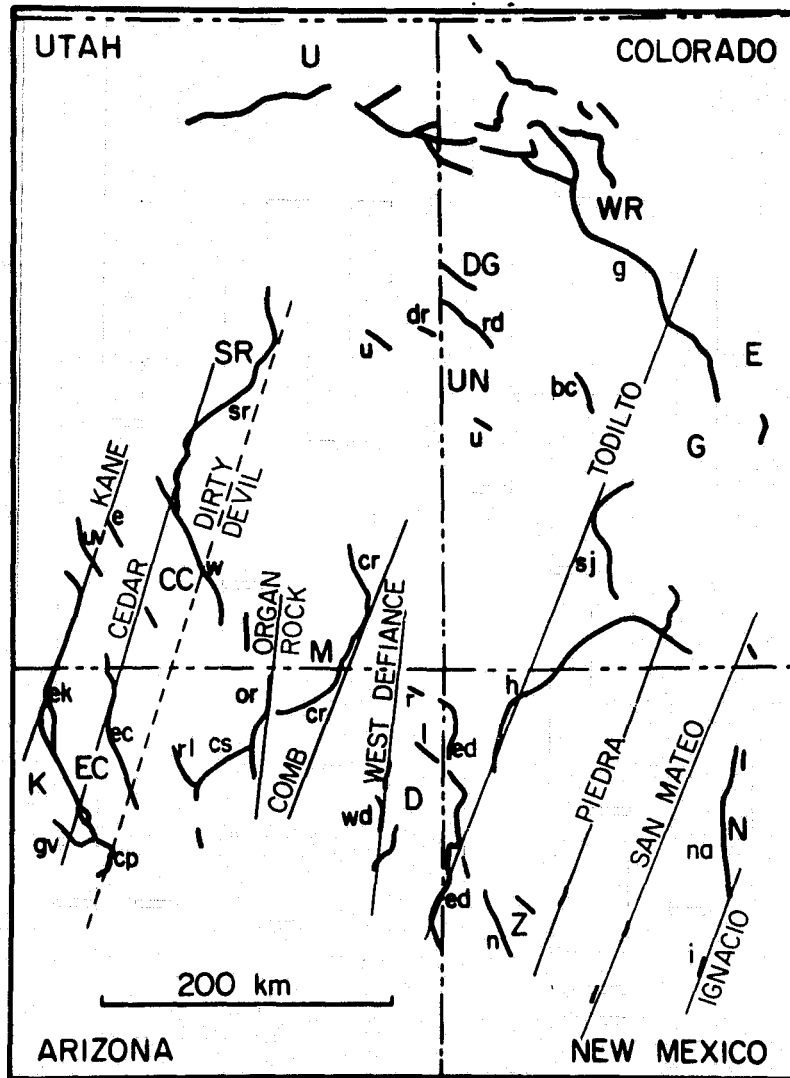


Figure 13. Map showing traces of the inferred NNE-striking fracture zones. Base map of monoclinial fold pattern from V. C. Kelley (1955b).

Figure 13, is expressed by NNE-trending aligned segments of the Additional Hill and San Rafael monoclines, although its effect on the Echo Cliffs and Waterpocket monoclines in between is minimal. The Organ Rock fracture zone includes the Organ Rock monocline and the SW projection of same; its orientation is askew of the preferred N. 20° E. trend. The Comb fracture zone coincides with the NNE-trending segment of the Comb Ridge monocline. The West Defiance zone, like the Organ Rock, strikes approximately N. 5° E.; it is the locus of segments of the West Defiance monocline. The inferred Todilto fracture zone is 400 km long and includes segments of the East Defiance, Hogback, and San Juan monoclines; it projects to a SW-convex bend in the Grand monocline. Southeast of the Todilto zone are the Piedra, San Mateo, and Ignacio fracture zones which are defined by aligned, short monocline segments. The inferred N. 20° E.-trending fracture zones would appear to be best developed in the southwestern and southeastern parts of the Colorado Plateau.

The N. 55° E.-striking fracture zones inferred from the monoclinial fold pattern (Figure 14) are for the most part defined on the basis of alignments of terminations of segments, and bends and branches of monoclines. However, some coincide in part with relatively long monoclinial segments. The San Rafael fracture zone projects from the NW terminus of the Upper Valley monocline, along the NE-trending segment of the San Rafael monocline, through the NW termini of the Cisco and Garmesa monoclines, to the abrupt NE-convex bend in the Grand monocline. The Ellen fracture zone extends from a bend in the East Kaibab monocline, through the SE terminus of the Upper Valley monocline, through the juncture of the San Rafael and Waterpocket monoclines, through the SE terminus of the Davis Ranch monocline, to a major SW-convex bend in the Grand monocline. The Snowmass fracture zone projects NE from the southern termination of the Kane Canyon structural terrace of the East Kaibab monocline, through a bend in the Echo Cliffs monocline, along the southeastern termini of the Waterpocket and Uncompahgre monoclines, the northern termini of the Balanced Rock, Comb Ridge,

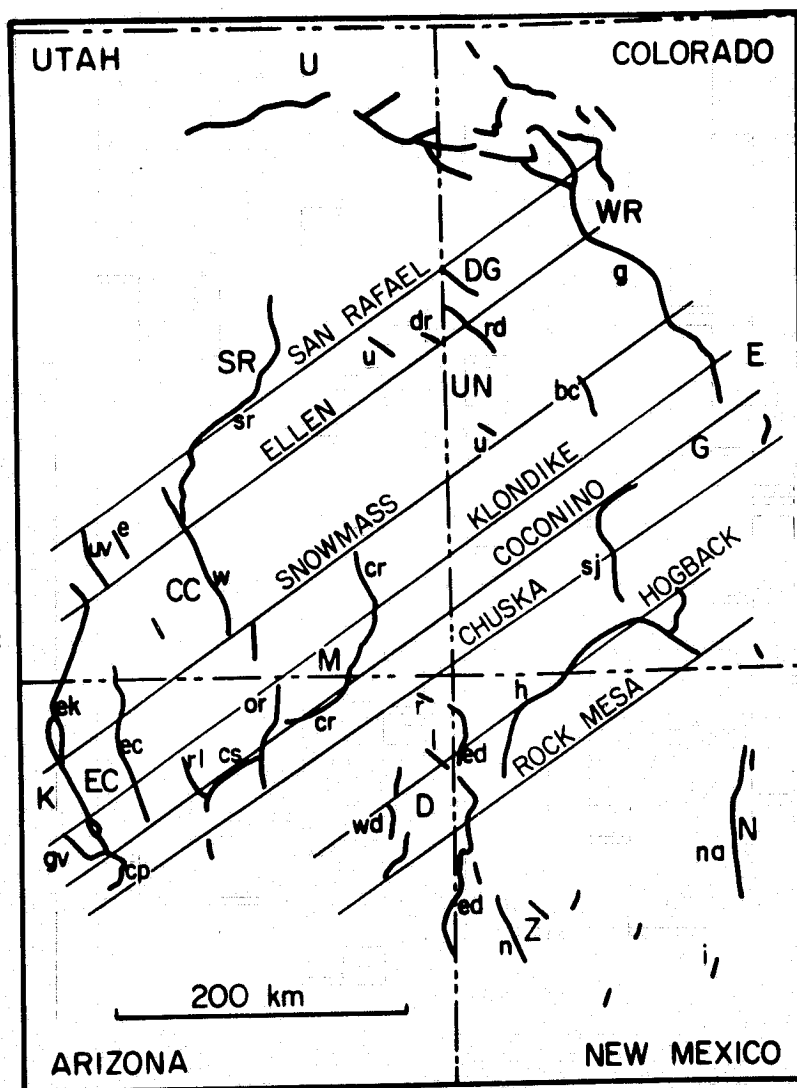


Figure 14. Map showing traces of the inferred NE-striking fracture zones. Base map of monoclinal fold pattern from V. C. Kelley (1955b).

and Gunnison monoclines, and through the SW-convex bend in the Grand monocline. The Klondike fracture zone passes through the northern termini of the Grandview, Cedar Mesa, Red Lake, and Organ Rock monoclinial segments, and projects through a major bend in the Comb Ridge monocline to a NE-convex bend in the Grand monocline. The Coconino fracture zone is the "type example" of the inferred N. 55° E. -trending fracture zones, and part of its length as defined herein corresponds to the Coconino lineament of Kelley (1955b). The Coconino zone includes the junction of the East Kaibab (1955b) and Grandview monoclines, the SE terminus of the Echo Cliffs monocline, the Red Lake - Cow Springs and Cow Springs - Organ Rock - Comb Ridge monocline junctures, the Cow Springs monocline, and segments of the Comb Ridge and San Juan monoclines. The Chuska fracture zone is conjectural and is inferred to comprise a segment of the Coconino Point monocline, the south terminus of the Organ Rock monocline, a bend in the San Juan monocline, and the south end of the Crookton monocline. The Hogback fracture zone projects NE from a break and apparent offset in the West Defiance monocline, through the SE terminus of the Lukachukai monocline, and along segments of the East Defiance and Hogback monoclines. The Rock Mesa fracture zone coincides with aligned segments of the West and East Defiance monoclines and marks the eastern terminus of the Hogback monocline.

The entire array of inferred NNW-, NW-, NNE-, and NE-striking fracture zones is presented in Figure 15. It is suggested that this array may reflect the characteristics (e.g. trend, spacing, and length) of that portion of the basement-fracture system of the Plateau that was to some extent active during monoclinial folding. The array of fracture zones represents a basement-fracture "subsystem" for the Plateau in that it lacks regional elements that have no apparent expression in the monoclinial fold pattern. Within the subsystem, during the time(s) of monoclinial folding, individual blocks moved differentially with respect to one another producing, where the force vectors, displacement magnitudes, and rock properties permitted, interblock folding.

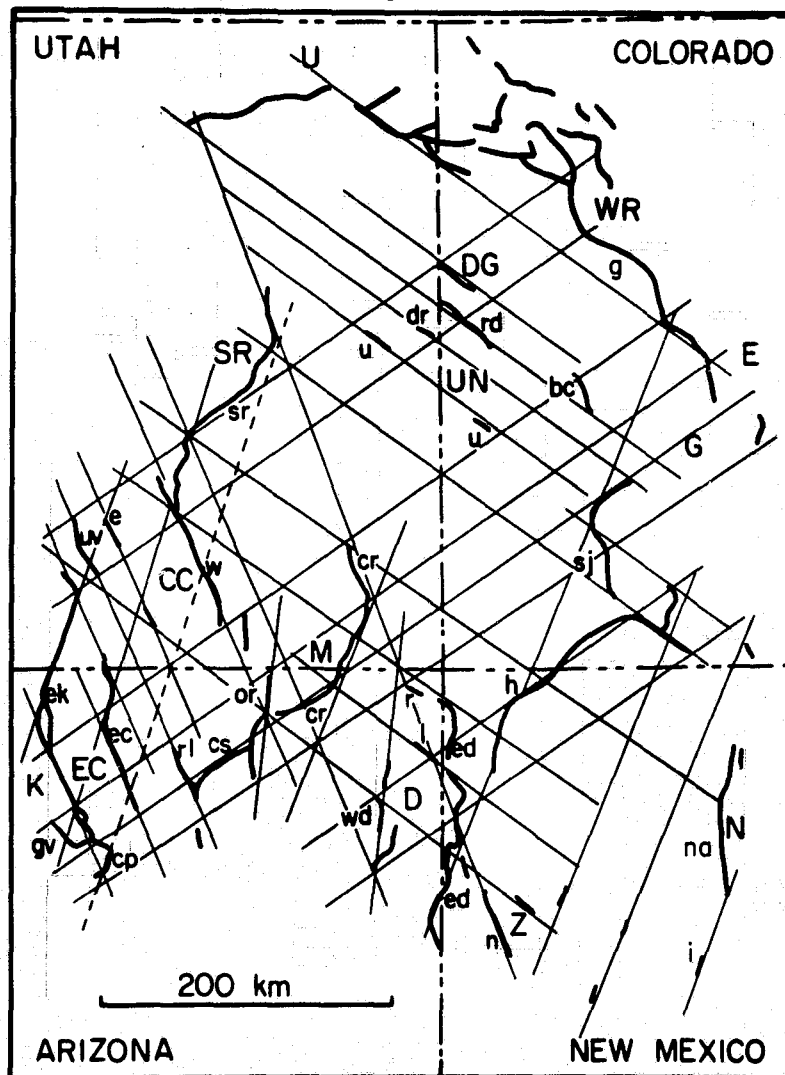


Figure 15. Map showing inferred fracture system for the Colorado Plateau. Base map of monoclinal fold pattern from V. C. Kelley (1955b).

Evidence for Deep-Seated Nature of the Inferred Fracture System

Several factors suggest that most of the inferred fracture zones are associated with deep-seated fault zones, some of which record major displacements. The clearest, most direct indication of this association is that most of the inferred fracture zones, by definition, are locally coincident with monoclinial segments of demonstrable movement ranging from several hundred to thousands of feet. Indirect support for the deep-seated nature of the inferred fracture sets is evident in the regional distribution of igneous centers and in regional geophysical data patterns.

Individual inferred fracture zones and intersections of inferred fracture zones are systematically related to some of the igneous centers of the Colorado Plateau (Figure 16). For example, in Utah the Heep Mountain intrusives comprise NNW-trending dikes which lie on the Henry zone and between the Henry and Waterpocket zones. Within the Henry centers, the Ellen stock lies on the intersection of the Henry and Ellen zones, the Pennel stock lies on the intersection of the Dirty Devil and Rattlesnake zones, and the Hillers stock occurs at the intersection of the Henry and Rattlesnake zones. The La Sal centers occur near the intersection of the Comb and Uncompahgre zones. In Colorado, the La Plata centers are close to and locally on the Todilto zone. Within the San Juan centers, the Wilson intrusive crops out near the intersection of the Todilto and Uncompahgre zones, and the Baldy Peak intrusive occurs at the intersection of the Davis Ranch and Coconino zones. In southern Colorado and northern New Mexico, a broad zone of NNE-trending dikes pervade the region between the San Mateo and Piedra zones. In Arizona, although plugs occur on the Red Lake zone, and dikes crop out at the intersection of the Comb and De Chelly zones, the relationship of igneous centers to the inferred fracture zones is in general poor.

Relation of Fracture Zones to Intrusive Bodies

1. Heep Mountain Intrusives
2. Ellen Stock
3. Pennel Stock
4. Hillers Stock
5. La Sal Centers
6. La Plata Centers
7. Wilson Intrusive
8. Baldy Peak
9. Navajo Centers

See Figure 16 on page 44.

INTRUSIVE BODIES

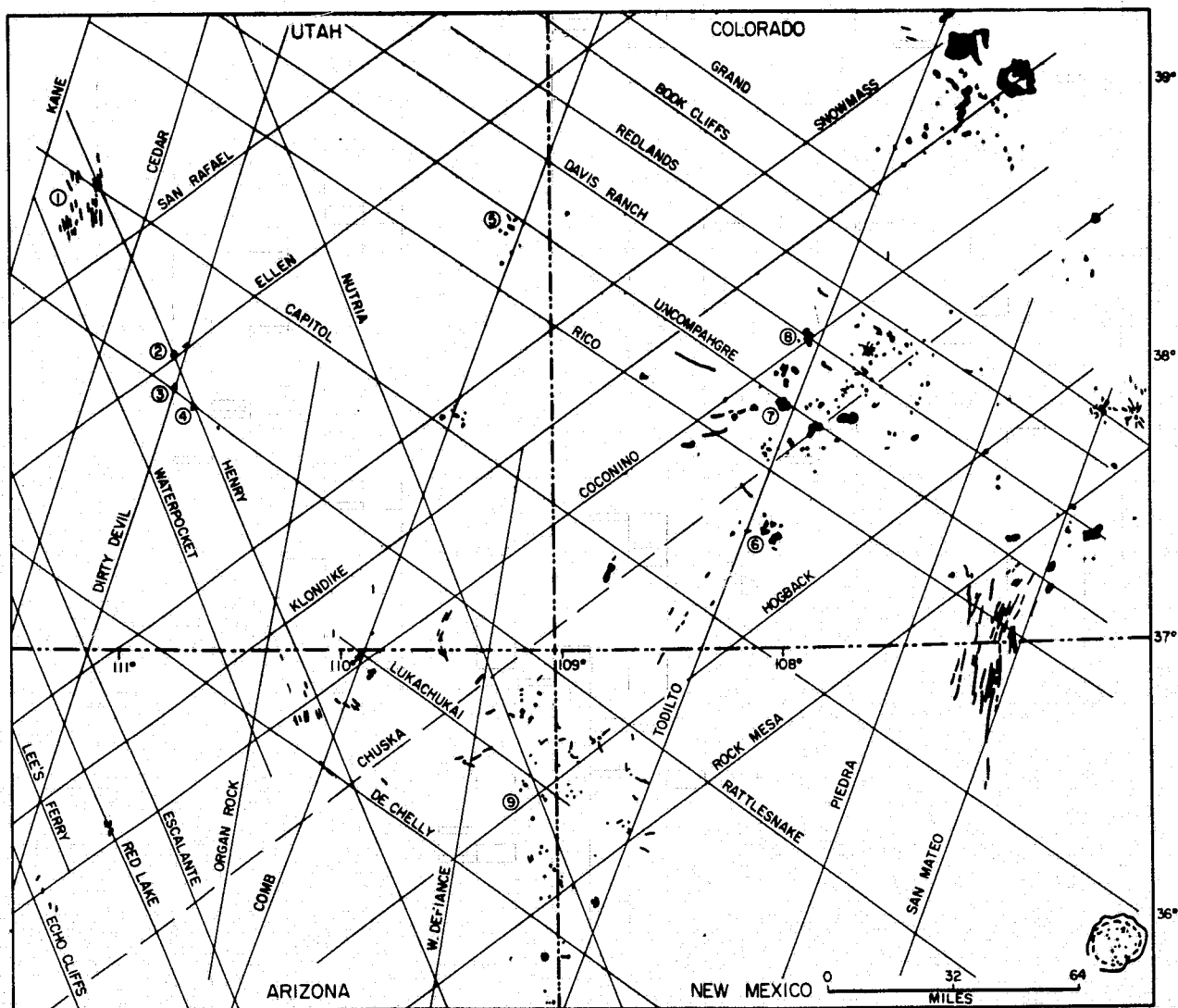


Figure 16. Map showing relationship of members of the inferred fracture system to the distribution of igneous centers in the Colorado Plateau. Map distribution of the igneous centers from Kelley (1955b), and Kelley and Clinton (1960).

The relationship of igneous centers of the Colorado Plateau to the composite inferred fracture-zone pattern seems to suggest that the loci of emplacement of some of the igneous bodies are related to the distribution and attitude of specific inferred fracture zones identified herein. If this is true, those fracture zones associated with the igneous rocks must be deep-seated. The NW, NNW, NNE, and NE sets shown in Figure 16 undoubtedly contain members that lack a monoclinial expression, but that nonetheless may have controlled the emplacement of some of the plutons, plugs, and dikes whose positions may seem aberrant with respect to the inferred fracture system.

Eastwood (1974) evaluated the distribution of volcanic activity in the southern part of the Colorado Plateau as it might relate to lineament tectonics. He identified two major trends of lineaments (N. 45° W. and N. 50° E.) based on the occurrence of volcanic fields, as well as one minor but persistent trend (N. 20° E.). These trends clearly correspond to three of the four inferred fracture trends recognizable on the basis of monoclinial folds, i. e., N. 55° W., N. 55° E., and N. 20° E. Eastwood (1974, p. 250) concluded:

"The persistence of volcanism and plutonism along two lineament systems throughout Cenozoic time suggests that they are ancient and large-scale tectonic features. Correlation of these directions with structural elements of Precambrian age in Precambrian rocks attests to their antiquity. Because magma of mantle origin occur along lineaments, these tectonic features therefore extend through the lithospheric crust and into the upper mantle, as suggested by Lipman and Moench (1972)."

Case and Joesting (1972) provide geophysical support for (1) the conceptual basis for the basement-block tectonic model of monoclinial folding as presented in this study as well as for (2) the reality of the inferred basement-fracture system deduced from application of the model. They examined regional gravity and aeromagnetic patterns within a major portion of the Colorado Plateau and noted that

the monoclinial uplifts are associated with gravity highs and high-amplitude magnetic anomalies bordered by relatively steep magnetic gradients. According to them (Case and Joesting, 1972, p. 10):

"The anomalies across the crests of the monoclinial uplifts are more heterogeneous than those over the adjacent structurally low areas, and this increased heterogeneity suggests a difference in Precambrian basement lithology, which may reflect the existence of Precambrian or late Paleozoic structural boundaries that were rejuvenated during the Laramide. ...the near-linear zones of steepened magnetic gradients and lines of discontinuities of anomalies persist many miles in parts of the region. These zones reflect major lithologic discontinuities within the Precambrian basement and probably indicate a fundamental fracture pattern of Precambrian age. ...dominant trends of these fracture zones are northwest, northeast, north, and east." (Emphasis added.)

They concluded, on p. 26:

"Where the gradients and geophysical discontinuities fall along lines, they clearly indicate faults in the basement; so, we may generalize that the basement pattern is one of fault blocks, which correspond to zones of nearly straight steepened gravity and magnetic gradients"

In the same paper, they show that the Precambrian fracture zones exerted a profound influence on Phanerozoic sedimentation, tectonism, and igneous activity. They cite subsurface evidence for the existence of post-Precambrian, pre-Pennsylvanian faults (or warps) with displacements of as much as 5000 feet. Within the Paradox basin, such faults have controlled the locus of emplacement not only of salt anticlines but also of elongate igneous intrusions. Furthermore, they note, the regionally extensive gravity and magnetic lineaments tend to intersect at most of the laccolithic centers.

Summarizing, the Colorado Plateau contains deep-seated, near-vertical zones of weakness, Precambrian in age, which serve to subdivide the Colorado Plateau into blocks.

During the Phanerozoic, these zones were subject to reactivation at various times, resulting in major faulting, monoclinial folding, and the structurally controlled emplacement of igneous bodies. At the surface, the tectonic adjustments of the blocks influenced the configuration of basins of sedimentation.

A basement-block tectonic model is perhaps what V. C. Kelley (1955a, p. 802) envisioned when he commented that the distribution and form of the monoclines of the Colorado Plateau may be influenced by a "mosaic of differing Precambrian subcrustal nuclei" whose "shapes approximate those of the variously oriented tectonic divisions at the surface." It is certainly what Hodgson (1965) must have had in mind when he noted that in the Grand Canyon region, "Maximum deformation of the rocks occurs along narrow, linear zones which appear to follow elements of a primordial fracture pattern in the Precambrian basement. Sedimentary rocks play a passive role in the formation of folds...." (p. 935). "The lack of uniform distribution of deformation in the rocks, coupled with the predominant vertical sense of the displacements, suggests ... differential vertical movements of discrete basement-blocks."

Inferred Basement-Fracture Pattern in the Colorado Plateau Tectonic Province of Arizona

The large-scale fold pattern within the Colorado Plateau tectonic province of Arizona clearly reveals basement control brought about by differential vertical movements along high-angle fracture zones. Plate II displays traces of the inferred basement-fracture zones which appear to have exerted the most profound control on the fold pattern. The prominent NW, NNW, NNE, and NE regional fracture directions, outlined above, are all represented. However, some of the fracture zones projected into Arizona on the basis of the regional analysis do not have obvious

expression in the folds. Conversely, the representation of short monoclinial segments, anticlines, and synclines on the structure map of folds in Arizona (Plate I) permit inferred fracture zones to be discerned which are not identifiable on the small-scale structure map of monoclines for the Plateau as a whole. It is presumed that detailed, large-scale investigations of any portion of the Colorado Plateau would reveal additional, systematically oriented and distributed fracture zones with a range in subtlety of expression.

Of those NNW-striking fracture zones recognized in the analysis of the Colorado Plateau as a whole, the Kaibab, Echo Cliffs, Lee's Ferry, Red Lake, and Escalante have some visible expression in Arizona (refer to Plates I and II throughout this discussion). The existence of the Escalante fracture zone in Arizona is the most questionable, but it may be evidenced in the short, curvilinear monoclinial segment at the northwest corner of Black Mesa just southwest of the Cow Springs anticline (Plate I). Additional NNW-striking fracture zones recognized include the Klagetoh and Hunters. The Klagetoh fracture zone includes the Klagetoh monocline and a segment of the Rock Mesa monocline. The Hunters fracture zone coincides in part with the Hunters Point segment of the East Defiance monocline.

NE-striking fracture zones recognized in the regional analysis which have some expression in the fold pattern of northern Arizona include the Snowmass, Klondike, Coconino, Chuska, Hogback, and Rock Mesa. The Snowmass fracture zone is defined on the basis of the short Wheeler monocline, the south end of the Kane Canyon structural terrace of the East Kaibab monocline, and the bend in the Echo Cliffs monocline. The Klondike fracture zone extends from the north end of the Cedar Mesa structural terrace of the East Kaibab monocline through the south termini of the Rainbow monocline, Rainbow anticline, Piute syncline, Balanced Rock anticline, and Nakai syncline. The Coconino fracture zone is a profound break and has been described above. It determines the SSE terminus of both the Kaibab syncline and the Echo Cliffs monocline. The Chuska fracture zone marks the south portion of the

Additional Hill monocline, the south terminus of the Red Lake monoclinal zone, the abrupt bend in the Big Mountain anticline, and is nearly coincident with the Tyende Creek syncline. The Hogback fracture zone is marked by an abrupt bend in the Sheep Creek monocline, the south termini of the Lohali syncline and the Black Mountain anticline, and the NW terminus of the Great Gleet anticline. The Rock Mesa fracture zone parallels the monocline of the same name. Many additional NE-striking inferred fracture zones can be identified using all of the folds on Plate I as a basis for control. The Jacob Lake fracture zone marks the north end of the Kane Canyon structural terrace of the East Kaibab monocline and may be expressed as the south terminus and bend of the West Kaibab monocline. The Dibe Chaa is an interesting fracture zone marked by a number of terminations. It passes through the NNW termini of the Mount Beautiful anticline and the Howell Mesa syncline, the NW termini of the Oraibi anticline and syncline, the "wishbone" junction of the Cow Springs anticline and the Big Mountain anticline, the south termini of the Big Mountain anticline and the Maloney syncline, the NW terminus of the Sheep Creek syncline, the SE termini of the Chilchinbito anticline and the Church Rock syncline, and the wishbone junction of the Red Rock and Sweetwater synclines. The Round Rock fracture zone extends SW from the Round Rock monocline through slight bends in the Tochee and Craibi monoclines. The Chinle fracture zone passes across the south terminus of the Chinle segment of the West Defiance monocline. The Ruin fracture zone is defined on the basis of the south terminus of the Ruin monocline and the north terminus of the Klagehoh monocline. Finally, a series of inferred fracture zones are recognized on the basis of aligned anticlines and synclines whose NE trend is anomalous with respect to the prevailing NW trend of most of the anticlines and synclines. These include the Painted Desert, Little Carrizo, and Beaver zones.

NW-striking inferred fracture zones are poorly represented in northern Arizona. The De Chelly fracture zone is expressed in a segment of the Sheep Creek

monocline, the Chilchinbito anticline, and a NW segment of the Oljeto syncline. The Lukachukai fracture zone, inferred to be NW-striking on the basis of the regional analysis, may strike in a north-northwesterly direction. It appears to bisect the convergence of the Walker Creek anticline and the Defiance anticline. An additional NW-trending zone, the Tochee, is marked by a segment of the Tochee monocline, the NE terminus of the Maloney syncline, and the complex zone of the deformation along the Cow Springs monocline.

NNE-striking inferred fracture zones in Arizona are fairly well developed. The Kane fracture zone is expressed in the NNE-trending segment of the East Kaibab monocline. The Cedar fracture zone is denoted by a major bend in the Grandview monocline, the east terminus of the Heather monocline, the NW margin of the Cedar Mesa structural terrace, the south termini of the Vermillion anticline and the Paria syncline, and a segment of the Echo Cliffs monocline. The Dirty Devil fracture zone is inferred to be represented merely by a portion of the Additional Hill monocline. The Organ Rock fracture zone is expressed in the Organ Rock monoclines as well as in a segment of the Big Mountain anticline. The Comb fracture zone splits the convergence of the Chinle Wash syncline and the Red Point Mesa anticline. The West Defiance fracture zone generally marks the locus of segments of the Rock Mesa, Chinle, and Sheep Creek monoclines. The Todilto fracture zone is expressed in Arizona only as relatively short segment of the East Defiance monocline.

The traces of the inferred fracture zones noted above are for the most part congruous with patterns expressed on the Residual Aeromagnetic Map of Arizona (Sauck and Sumner, 1971). Over portions of the lengths of many of the inferred fracture zones, the fracture-zone traces tend to be subparallel to contour trends (Figure 17). In addition, segments of many of the inferred fracture zones (1) pass through magnetic highs, (2) outline domains of aberrant contour trend, (3) split adjacent, subcircular magnetic highs, and (4) correspond to steep magnetic

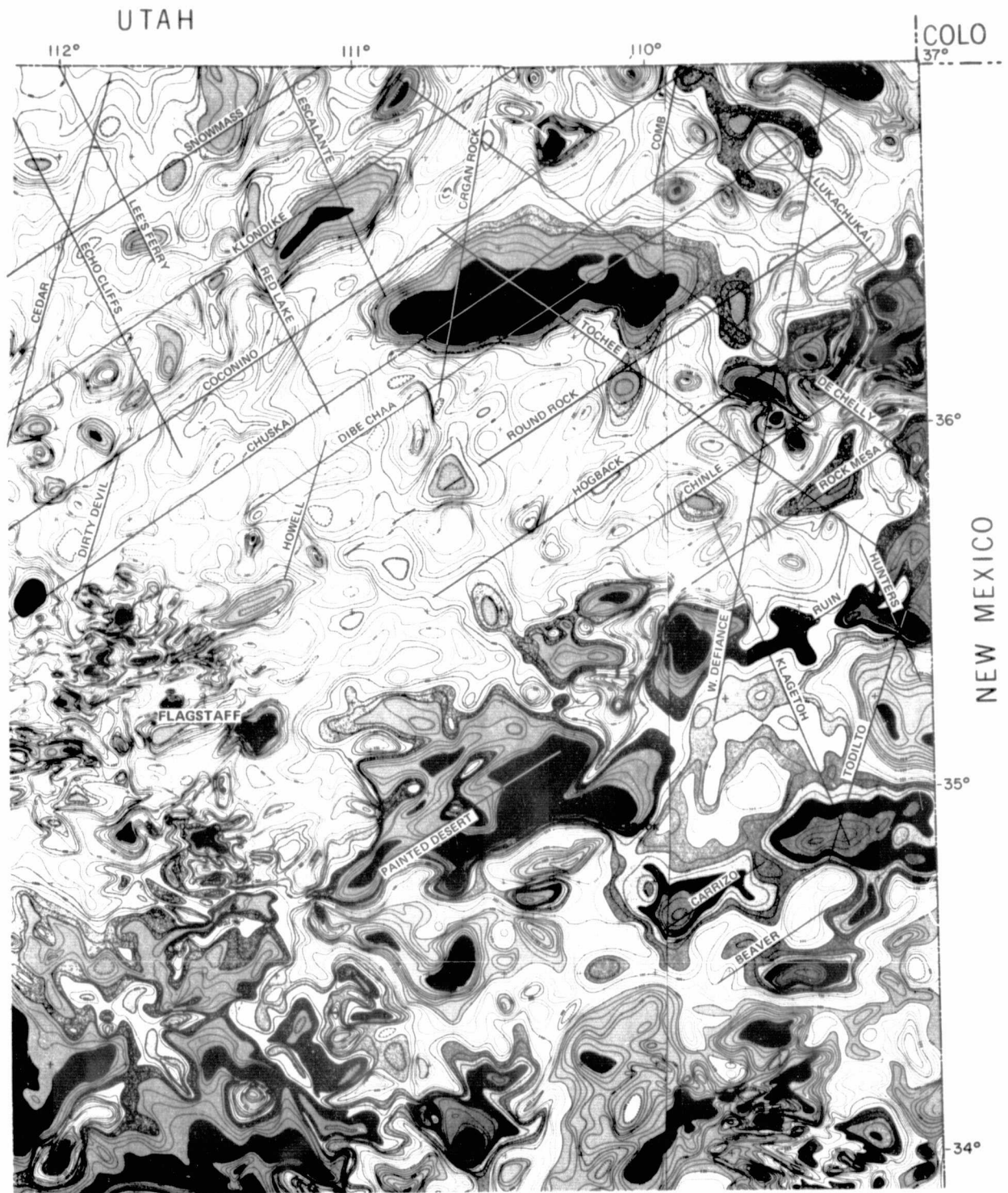


Figure 17. Inferred fracture-zone system for a portion of the Colorado Plateau tectonic province of Arizona superimposed on the residual aeromagnetic map of Sauck and Sumner (1971).

gradients. Detailed comparisons of the residual aeromagnetic contour pattern to surface-expressed structural and photogeologic patterns might afford optimum positioning and projection of the inferred fracture zones. Such an approach has been employed successfully by Shoemaker and others (1974) for the Bright Angel and Mesa Butte fault systems of northern Arizona.

RELATIONSHIP OF INFERRED FRACTURE SYSTEM TO THE DISTRIBUTION OF OIL AND GAS

Evidence has been presented that the Colorado Plateau tectonic province is cut by systematically aligned, regional fracture zones which subdivide the Plateau into a mosaic of crustal blocks. The fracture zones are thought to have originated in Precambrian time. They exerted structural control on Laramide and middle to late Cenozoic tectonism, including folding, faulting, volcanism, and plutonism, and it is likely that they influenced Paleozoic and Mesozoic depositional patterns. From the perspective of structural geology, the fracture zones are narrow, linear belts of concentrated strain which separate crustal blocks that are essentially undeformed. The monoclinal downbends are spectacular examples of such concentrated strain in which the deformation was achieved by folding. From the stratigraphic perspective, the fracture zones probably correspond locally to narrow, linear belts marking facies and thickness changes within Paleozoic and Mesozoic stratigraphic units, but this hypothesis was not tested in this study. Physically, the regionally persistent inferred fracture zones commonly consist of anomalously highly fractured strata that are folded or homoclinal; stratigraphic units in the vicinity of these zones may display complex facies variations. Diapirs of igneous rock and salt have been emplaced into many of the zones of crustal weakness.

The distribution of oil and gas pools in the Colorado Plateau bears a correspondence to elements within the system of inferred fracture zones. This is not surprising in view of the probable geologic characteristics of these fracture zones, particularly the high degree of fracturing, the profound deformation by folding and faulting, and the presumed facies changes. Given the existence of source layers for oil and gas within a rock system, rock fracturing may aid in the migration of the fluids, and

sedimentary and structural complexities may be conducive to entrapment. Furthermore, the nature of the basement-fracture system envisioned for the Colorado Plateau, and the prolonged history of differential vertical movements within the system, favors the phenomenon of cross folding, particularly in the vicinity of fracture intersections. For example, anticlines or monoclines formed by differential vertical movements along one fracture zone may be transformed into domes or doubly plunging anticlines by a superposed differential vertical movement along a proximate fracture zone of different strike (see Ramsay, 1962, 1967; O'Driscoll, 1962). An example of one type of cross folding is found on the middle limb of the East Defiance monocline, where the NE-striking, SE-dipping limb is refolded about SE-plunging anticlines and synclines (Plate I). Woodward (1973, p. 97) has interpreted these cross folds as a zone of drag folding caused by a major shifting of the western part of the Colorado Plateau to the northeast (as a response to the "westward drift of the North American plate over an eastward-dipping subduction zone ... along the eastward edge of the oceanic Farallon plate"). Using the model derived herein, the cross folds are more simply interpreted as an interference product of SE-directed high-angle reverse faulting along the Todilto fracture zone and SW-directed reverse faulting along the Nutria fracture zone.

Thomas (1974) has demonstrated that "lineament-block tectonics" exerted profound control on oil and gas entrapment within the Williston-Blood Creek basin. He observes (p. 1319): "... the subblocks defined by the weakness zones can be coupled by orogenic forces to form intrablock folds. ... these folds and lineaments in turn ... can influence the development of paleotopographic highlands and subbasins within the regional basinal area, thereby affecting shelf development and trend. Paleostrand lines, facies changes, and thickness variations may, in turn, be 'controlled' by this shelf development on the flanks of the highlands and subbasins and along lineaments. Because these weakness zones are the same tectonically mobile zones producing drag folds in the stratigraphic section, it is logical to find

many oil and/or gas localizations in proximity to the weakness zones in addition to those fields surrounding or within drag folds."

Figure 18 shows the distribution of oil and gas pools and salt anticlines in the Paradox and San Juan basins based on maps presented in the Geologic Atlas of the Rocky Mountain Region (Rocky Mountain Association of Geologists, 1972, p. 283 and 285). In addition, Figure 18 provides the distribution of the oil and gas fields in Arizona (Conley, 1975). Traps for the control of oil and gas pools in the rocks of the Plateau are both stratigraphic and structural. For example, in the southern part of the Paradox basin, major production is derived from primarily stratigraphically controlled Pennsylvanian reservoirs whereas in the northern part of the basin, the controls are primarily structural, including domes, anticlines, and faulted, homoclinal strata (Rocky Mountain Association of Geologists, 1972). In the central portion of the San Juan basin, the controls for oil and gas are primarily hydrodynamic, but on the western margin of the basin the major controls include structural elements, particularly domes and anticlines. In northeastern Arizona, the most productive zones for oil and gas are within the Hermosa Group of Pennsylvanian age (Conley, 1974) with trapping aided by the presence of anticlines and domes. The greatest production in Arizona has been derived from Dineh-bi-Keyah, an unusual field in which the reservoir is a Tertiary igneous sill in the Pennsylvanian strata (Peirce and others, 1970).

Many oil and gas fields in the Colorado Plateau are spatially associated with the regional fracture zones delineated in this study. Within the Paradox basin, the McElmo Dome, Tohonadla, Gothic Mesa, Aneth, Andy's Mesa, SE Lisbon, Big Indian, and Lisbon fields all appear to be spatially, and perhaps genetically, linked to specific fracture zones (Figure 18). The McElmo Dome gas field lies on the Capitol fracture zone. Both the Tohonadla and Gothic Mesa fields lie on or close to the Coconino, and the Aneth field occurs near the intersection of the West Defiance and Coconino fracture zones. In western Colorado, the Andy's Mesa field is elongate N. 55° W. and occurs

1. McElmo Dome
2. Tohonadla
3. Gothic Mesa
4. Aneth
5. Andy's Mesa
6. SE Lisbon
7. Big Flat
8. Big Indian
9. Lisbon
10. Tocito Dome
11. Table Mesa
12. Rattlesnake
13. Hogback
14. Horseshoe Canyon
15. Many Rocks
16. Bisti
17. Escrito
18. Dineh-bi-Keyah
19. Bita Peak, Teec Nos Pos,
Twin Falls Creek
20. East Boundary Butte, North
Toh-Atin
21. Dry Mesa, Black Rock

OIL & GAS POOLS
SALT ANTICLINES

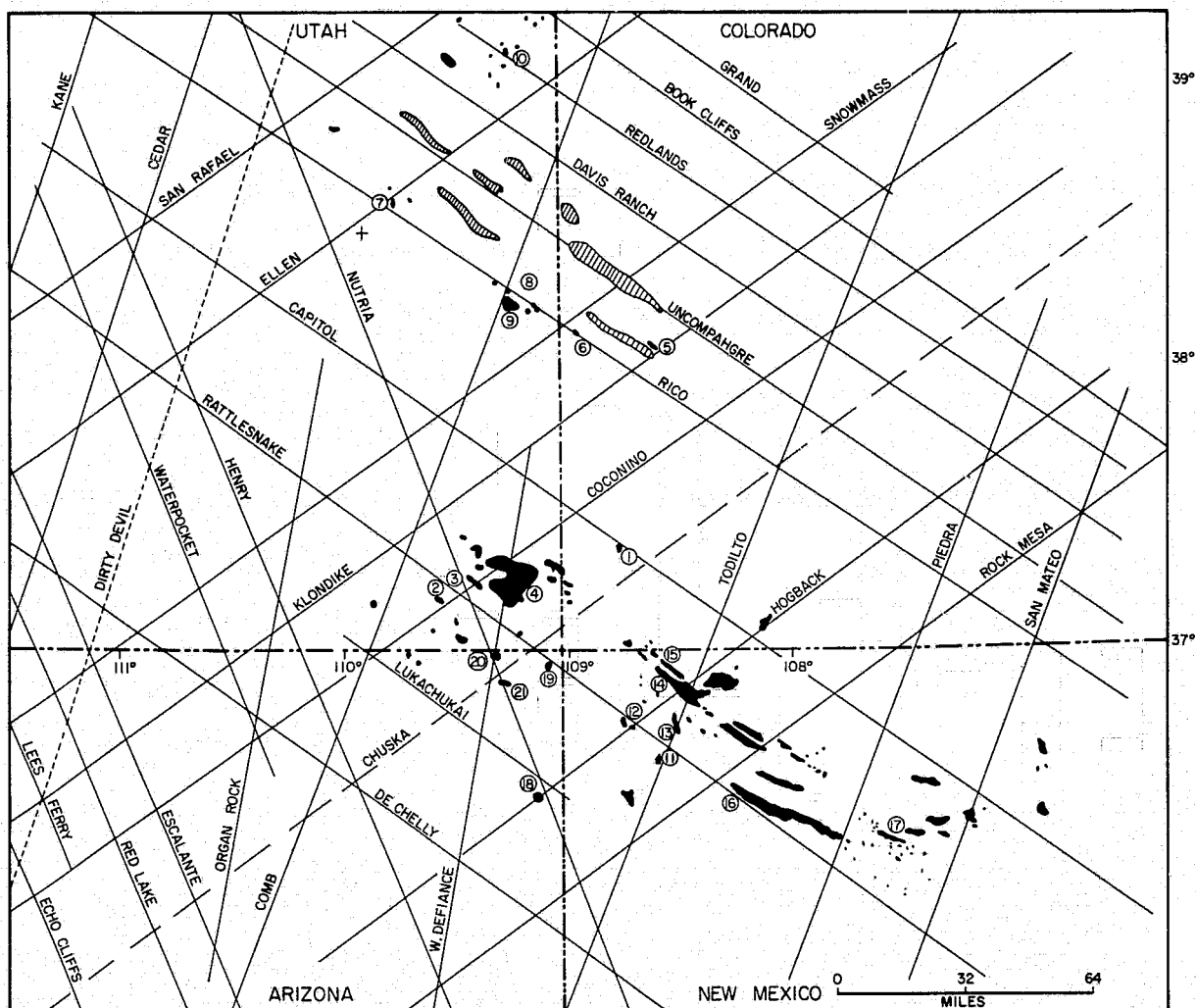


Figure 18. Map showing relationship of the members of the inferred fracture system of the Colorado Plateau to the distribution of oil and gas pools and salt anticlines in the Paradox and San Juan basins. Distribution of oil and gas pools and salt anticlines from Rocky Mountain Association of Geologists (1972) and Conley (1975). Oil and gas pools shown in black. Close-spaced line pattern indicates location of salt anticlines.

on the Klondike fracture zone, and the SE Lisbon field lies on the Rico fracture zone. In east-central Utah, the Big Indian field is on the intersection of the Comb and Rico fracture zones, and the Lisbon field occurs near that same intersection. The Agate field is associated with the Redlands zone.

On the western margin of the San Juan basin, the Table Mesa field occurs on the Todilto fracture zone, near the intersection with the Rattlesnake fracture zone. The Rattlesnake oil and gas field occurs at the intersection of the Hogback and Rattlesnake fracture zones, and the Hogback field is on the Todilto fracture zone. The Horseshoe Canyon field is near the intersection of the Hogback and Todilto fracture zones, with several other fields, including Many Rocks, on a line trending N. 55° W. from that intersection. Within the central portion of the San Juan basin, the oil and gas fields are parallel to the N. 55° W. fracture-zone direction. The Bisti field lies on and just northeast of the Rattlesnake fracture zone. Most other fields within the central portion "of the basin" are contained between the Capitol and Rattlesnake fracture zones and are elongate northwesterly. Based on the distribution of oil and gas fields, it appears that a regional fracture zone lacking expression in the monoclinial fold pattern might extend S. 55° E. from the Horseshoe Canyon field through the Escrito field in New Mexico.

The oil and gas fields discovered in Arizona occur in the northeastern part of the State and most appear to be systematically disposed with respect to the major fracture zones (Figure 18). The Dineh-bi-Keyah field occurs on the Hogback fracture zone with its intersection with the Nutria and Lukachukai fracture zones. The Bita Peak/Teec Nos Pos/Twin Falls Creek field is on the Rattlesnake fracture zone. The East Boundary Butte/North Toh-Atin field is at the intersection of the West Defiance and Nutria fracture zones. Finally, the Dry Mesa/Black Rock field is on the Nutria fracture zone.

In regard to oil and gas exploration in Arizona, Peirce and others (1970, p. 99) commented:

"... there are no recognized geologic trends for explorationists to follow that lead away from the immediate Four Corners producing region. As a consequence, with the exception of the helium producing area, the remainder of the State can be classed as rank wildcat country. The drilling rate in Arizona away from the Four Corners region is low, which suggests that the industry is awaiting some form of encouragement to look further. Because so much of Arizona is untested there are large gaps in knowledge concerning important geologic details. Under these circumstances encouragement to take a closer look can come only from a favorable assessment of one or more of the broader aspects of the geologic framework."

It is hoped that the apparent spatial relationship of many of the oil and gas fields in the Colorado Plateau tectonic province to elements of the independently derived fracture-zone system discussed herein may represent a form of the "encouragement." Application of the basement fracture model proposed herein, through integrated studies involving seismic gravity, and magnetic geophysical analysis, subsurface structural and isopachous investigations, facies mapping, photogeologic/geomorphic mapping, and lineament analysis utilizing LANDSAT imagery, should lead to the identification of oil and gas exploration targets.

CONCLUSIONS

Structural mapping and analysis of folds in Phanerozoic rocks in northern Arizona has led to the formulation of a tectonic model for the specification of regional fracture zones within the Colorado Plateau as a whole. The monoclinical fold pattern in the Colorado Plateau tectonic province is interpreted to have resulted from differential vertical movements along reactivated high-angle faults of inferred Precambrian age. Because each monocline is the upper crustal expression of a discrete basement-fracture zone, the monoclinical fold pattern, in total, expresses the nature of the Colorado Plateau basement-fracture system. The major fracture sets, as deduced from the predominant trends of the monoclinical folds, strike N. 20° W., N. 55° W., N. 20° E., and N. 55° E. The Plateau itself may be envisioned as composed of an assemblage of polyhedra whose steeply dipping faces correspond to major fracture zones.

During the Phanerozoic, the regional fracture zones of the Colorado Plateau were subject to reactivation at various times, resulting in major faulting, monoclinical folding, and the structurally controlled emplacement of igneous bodies. At the surface, the tectonic adjustment of the various "blocks" probably influenced sedimentation patterns and the resultant facies distribution.

As loci of major fracturing, folding, and "rapid" facies changes, the inferred fracture zones may have exerted some control on the entrapment of oil and gas. A spatial and presumed genetic association exists between many of the oil and gas pools in the Paradox basin and the San Juan basin to members of the inferred regional fracture system for the Plateau. Virtually all of the oil and gas fields in Arizona are positioned on the traces of fracture zones. Work in progress suggests that uranium distribution on the Plateau may also be systematically disposed, to

some extent, with respect to the major fracture zones (Figure 19). Finally, as "lines" of repeated tectonic movements, the fracture zones deduced from the monoclinial fold pattern may be important elements in the evaluation of the seismotectonics of a major portion of the western United States.

URANIUM DEPOSITS

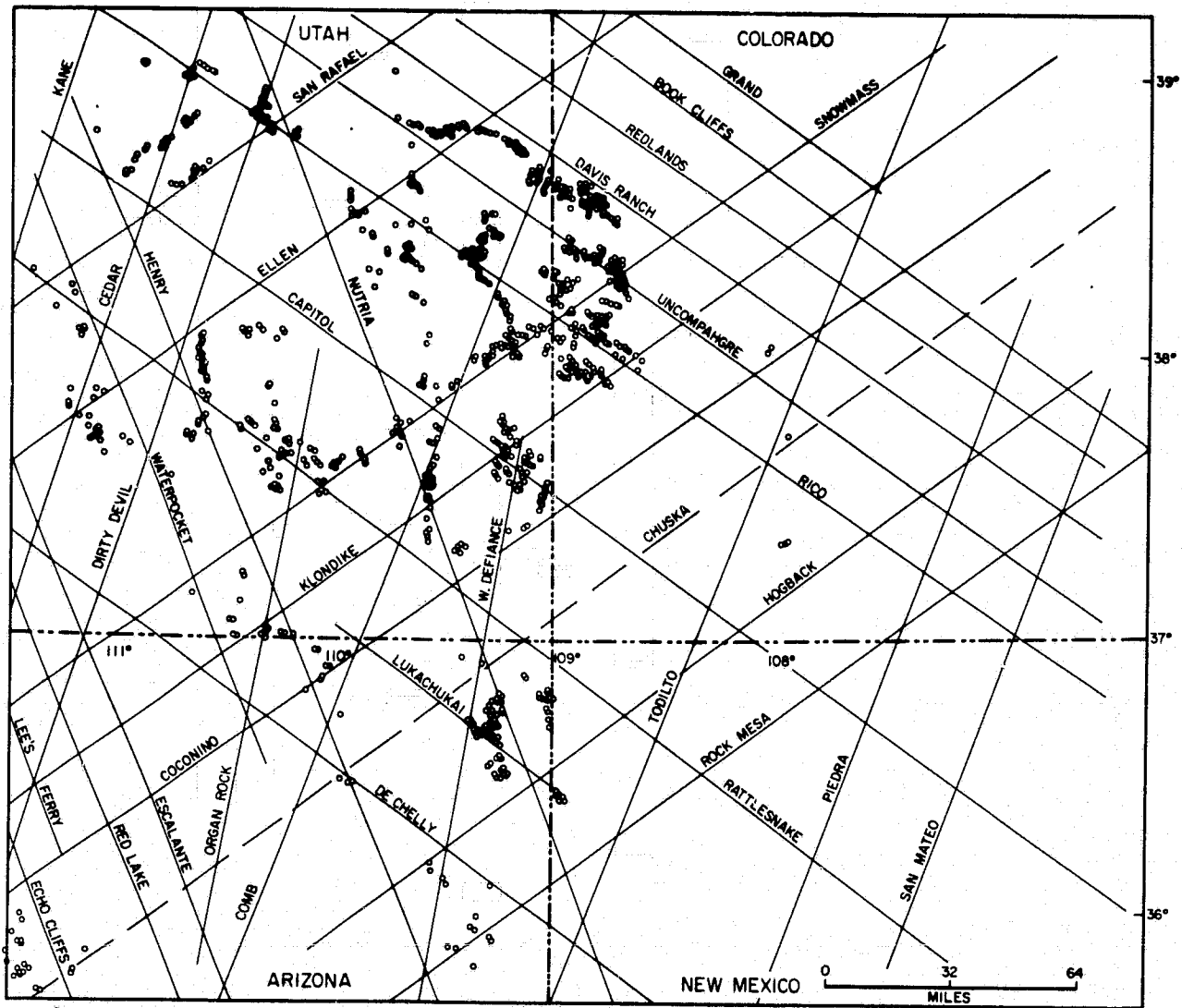


Figure 19. Map showing array of members of the inferred fracture system of the Colorado Plateau and the distribution of uranium deposits. Map of distribution of uranium deposits from V. C. Kelley (1955b).

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